

**A TECHNO-ECONOMIC EVALUATION  
OF THE GEODESIC DOME AS A  
POSSIBLE FORM OF LOW-INCOME  
HOUSE IN SOUTHERN AFRICA**

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## CONTENTS

### Page

|                                |      |
|--------------------------------|------|
| List of Figures .....          | i    |
| List of Working Drawings ..... | iv   |
| List of Illustrations .....    | iv   |
| List of Tables .....           | vi   |
| List of Schedules .....        | vii  |
| List of Programmes .....       | vii  |
| List of Maps .....             | vii  |
| Abstract .....                 | viii |

|                    |   |
|--------------------|---|
| INTRODUCTION ..... | 1 |
|--------------------|---|

### SECTION A

#### CHAPTER 1 : Traditional Black African Shelter

|            |   |    |
|------------|---|----|
| 1.1        | Introduction : Psychology of the Dome .....         | 4  |
| 1.2        | Classification of Traditional African Shelter ..... | 7  |
| 1.2.1      | The 'beehive' dome of the Nguni-speakers .....      | 8  |
| 1.2.2      | The 'sparrow-pot' cone of the Sotho-speakers .....  | 11 |
| 1.3        | Development of House Form .....                     | 12 |
| References | .....   | 15 |

#### CHAPTER 2 : Low-income Housing Policy in South Africa

|           |   |    |
|-----------|---|----|
| 2.1       | Defining the 'Housing Problem' : Population Growth, Urban Growth, Poverty ..... | 16 |
| 2.1.1     | Introduction .....  | 16 |
| 2.1.2     | Population Growth .....   | 17 |
| 2.1.3     | Urban Growth .....  | 22 |
| 2.1.4     | Poverty .....   | 26 |
| 2.1.4.1   | National Affordability .....  | 26 |
| 2.1.4.2   | Individual Affordability .....  | 30 |
| 2.1.4.2.1 | Black Incomes .....   | 31 |
| 2.1.4.2.2 | Housing Costs .....   | 36 |
| 2.2       | Low-income Housing Policy Developments : 1980-1984..                            | 39 |
| 2.2.1     | Introduction : Financing of Low-income Housing ....                             | 39 |

|   | Page |
|---|------|
| 2.2.2 State Subsidised Low-income Housing : 1980 .....                    | 41   |
| 2.2.3 Low-income Housing Policy Adjustments : 1982 .....                  | 45   |
| 2.2.3.1 Decentralisation Policy Adjustment .....                          | 46   |
| 2.2.3.2 'Self-help' Building .....  | 46   |
| 2.2.4 Low-income Housing Policy Adjustments : 1983 .....                  | 50   |
| 2.2.4.1 Priority Reallocation : Provision of more<br>Serviced Sites ..... | 51   |
| 2.2.4.2 Sales Campaign : 500 000 Dwelling Units .....                     | 52   |
| 2.2.5 Conclusion .....  | 55   |
| 2.3 Industrialised Housing : An Alternative .....                         | 57   |
| References .....  | 62   |

## SECTION B

|   |    |
|---|----|
| CHAPTER 3 : <u>The Geodesic Dome : Historical</u> ..... | 67 |
| References .....  | 85 |

## CHAPTER 4 : The Geodesic Dome : Methods of Construction

|   |     |
|---|-----|
| 4.1 Introduction .....                                  | 86  |
| 4.2 Types of Domes .....                                | 87  |
| 4.2.1 Strut-and-Skin Domes .....                        | 87  |
| 4.2.1.1 Strut Details .....                             | 88  |
| 4.2.1.2 Hub Systems .....                               | 90  |
| 4.2.1.2.1 Tube and Strap Hub .....                      | 90  |
| 4.2.1.2.2 Exposed Washer or Plate Hub .....             | 94  |
| 4.2.1.2.3 Concealed Washer or Plate Hub .....           | 98  |
| 4.2.1.2.4 'Fixed Axial Angle' Tube and Channel Hub .... | 99  |
| 4.2.1.2.5 'Fixed Axial Angle' Plate Hub .....           | 100 |
| 4.2.1.2.6 'Fixed Face Angle' Steel Strap .....          | 101 |
| 4.2.1.2.7 Flexible Flat Hub .....                       | 102 |
| 4.2.1.3 Skinning and Sealing Strut-and-Skin Domes ..... | 105 |
| 4.2.1.3.1 Plywood .....                                 | 106 |
| 4.2.1.3.2 Fibre-reinforced Cement .....                 | 113 |
| 4.2.1.3.3 Sheet Metal .....                             | 115 |
| 4.2.2 Panel Domes .....                                 | 115 |
| 4.2.2.1 Timber-framed Panels .....                      | 116 |
| 4.2.2.2 Flanged Panels .....                            | 118 |
| 4.2.2.3 Moulded Panels .....                            | 121 |

| <b>CHAPTER 5 : <u>The Design and Construction of Prototype, Dome A</u></b> |   | <b>Page</b> |
|--|---|-------------|
| 5.1  | Introduction .....  | 123         |
| 5.2  | Vital Statistics and Working Drawings .....   | 125         |
| 5.3  | The Foundations .....   | 139         |
| 5.4  | The Superstructure .....  | 142         |
| 5.4.1  | The 'Standard Shell' .....  | 143         |
| 5.4.1.1  | Manufacture of Panels .....   | 144         |
| 5.4.1.2  | Assembly .....  | 149         |
| 5.4.2  | 'Special Panels' .....  | 157         |
| 5.4.2.1  | 'Closure' Panels .....  | 158         |
| 5.4.2.2  | 'Window' Panels .....   | 160         |
| 5.4.2.3  | 'Door' Panels .....   | 166         |
| 5.4.2.4  | 'Ventilation' Panels .....  | 168         |
| 5.4.3  | Sealing the Dome .....  | 170         |
| <br><b>CHAPTER 6 : <u>Alternative Geodesic Design</u></b>                  |   |             |
| 6.1  | Dome B : 3-frequency Geodesic, 5/8-sphere, Icosa-<br>Alternate 'Truncatable' Breakdown, Vertex-zenith ..... | 175         |
| 6.2  | Dome C : 4-frequency Geodesic, 1/2-sphere, Icosa-<br>Triacon Breakdown, Edge-zenith .....                   | 176         |
| 6.3  | Dome D : 4-frequency Geodesic, 1/2-sphere, Octa-<br>Alternate Breakdown, Vertex-zenith .....                | 177         |
| 6.4  | Dome E : Triacantahedral Zome .....   | 178         |
| References   | .....   | 182         |
| <br><b>CHAPTER 7 : <u>Evaluation of Prototype Dome A</u></b>               |   |             |
| 7.1  | Environmental Performance .....   | 183         |
| 7.1.1  | Thermal Performance .....   | 183         |
| 7.1.1.1  | Introduction : Thermal Comfort .....  | 183         |
| 7.1.1.2  | Heat Mechanics, Thermal Properties of Materials<br>and Thermal Performance of Buildings .....               | 185         |
| 7.1.1.2.1  | Radiation, Solar Exposure and Fenestration ...  | 185         |
| 7.1.1.2.2  | Conduction, Insulation and Heat Capacity .....  | 188         |
| 7.1.1.2.3  | Air Movement, Convection and Ventilation ....   | 190         |
| 7.1.1.2.4  | Relative Humidity and Condensation .....  | 192         |
| 7.1.1.3  | Thermal Performance of Dome A .....   | 194         |
| 7.1.1.3.1  | Conduction .....  | 194         |
| 7.1.1.3.2  | Radiation .....   | 195         |
| 7.1.1.3.3  | Convection .....  | 196         |
| 7.1.1.3.4  | Condensation .....  | 196         |

|   | Page |
|---|------|
| 7.1.2 Moisture Exclusion .....                      | 198  |
| 7.1.3 Natural Illumination .....                    | 199  |
| 7.2 Structural Considerations .....                 | 199  |
| 7.2.1 Integrity .....                               | 199  |
| 7.2.2 Ease and Speed of Construction .....          | 202  |
| 7.2.3 Natural Extensions or Additions .....         | 203  |
| 7.2.4 Internal Subdivision .....                    | 208  |
| 7.3 Cost Analysis .....                             | 209  |
| 7.3.1 Introduction .....                            | 209  |
| 7.3.2 Labour Cost .....                             | 211  |
| 7.3.2.1 Manufacture .....                           | 213  |
| 7.3.2.2 Foundations .....                           | 215  |
| 7.3.2.3 Superstructure .....                        | 221  |
| 7.3.2.4 Summary of Total Labour Cost per Dome ..... | 224  |
| 7.3.3 Material Cost .....                           | 225  |
| 7.3.4 Summary of Costs per Dome .....               | 226  |
| References .....                                    | 227  |
| CONCLUSION .....                                    | 228  |

## APPENDIXES

### APPENDIX A A Brief Historical Account of Bantu Migrations and Settlements in Southern Africa

|  |     |
|--|-----|
| A.1 Introduction .....                     | 231 |
| A.2 Early Migrations and Settlements ..... | 232 |
| A.3 Cross-Cultural Contamination .....     | 234 |
| A.4 The Difaqane and its Aftermath .....   | 235 |
| References .....                           | 242 |

### APPENDIX B Geodesic Maths : 'Energetic Geometry'

|   |     |
|---|-----|
| B.1 A Brief Introduction to Richard Buckminster Fuller's Philosophy ..... | 243 |
| B.2 The Closest-packing of Spheres .....                                  | 247 |
| B.3 Elementary Polyhedral Geometry .....                                  | 251 |
| B.4 Great Circles of the Icosahedron .....                                | 256 |
| B.5 Spherical Trigonometry .....  | 259 |
| B.5.1 Introduction .....  | 259 |
| B.5.2 Angles of the Planar-faceted Icosahedron .....                      | 260 |

|   | Page    |
|---|---------|
| B.5.2.1            Face Angles and Central Angles .....                                     | 260     |
| B.5.2.2            Axial Angles .....   | 262     |
| B.5.2.3            Dihedral Angles .....  | 262     |
| B.5.3              Face Angles of the Spherical Icosahedron .....                           | 263     |
| B.5.4              Napier's Rule .....  | 263     |
| B.5.5              Application of Napier's Rule to Solve Great Circles ..                   | 265     |
| B.6                Geodesic Breakdowns .....  | 269     |
| B.6.1              Introduction .....   | 269     |
| B.6.2              The 'Triacon' Breakdown .....  | 270     |
| B.6.3              The 'Alternate' Breakdown .....  | 273     |
| B.6.4              'Triacon' versus 'Alternate' .....                                       | 275     |
| B.7                Examples of Chord Factor Calculations by Means of<br>Napier's Rule ..... | 279     |
| B.7.1              Using a 3-frequency Alternate Breakdown : Dome A                         | 279     |
| B.7.2              Using a 4-frequency Triacon Breakdown : Dome C ..                        | 281     |
| References .....  | 283     |
| <br>BIBLIOGRAPHY .....  | <br>284 |

## LIST OF FIGURES

|   | Page |
|---|------|
| 1.1 'Indhlu' dome framework (Zulu) .....                        | 9    |
| 1.2 Xhosa dome framework .....                                  | 10   |
| 1.3 'Sparrow-pot' cone framework (Sotho) .....                  | 11   |
| <br><u>Strut-and-Skin Domes</u>                                 |      |
| 4.1 Strut details : splay-cut .....                             | 88   |
| 4.2 Ditto : mitre-cut .....                                     | 89   |
| 4.3 Ditto : compound splay-mitre-cut .....                      | 89   |
| 4.4 Ditto : bevel-cut .....                                     | 89   |
| 4.5 Tube and strap hub .....                                    | 91   |
| 4.6 Ditto .....   | 91   |
| 4.7 Ditto .....   | 92   |
| 4.8 Ditto .....   | 93   |
| 4.9 Ditto .....   | 94   |
| 4.10 Ditto .....  | 94   |
| 4.11 Exposed washer or plate hub .....                          | 95   |
| 4.12 Ditto .....  | 95   |
| 4.13 Ditto .....  | 96   |
| 4.14 Ditto : Hubs of a 3-frequency alternate design .....       | 98   |
| 4.15 Ditto .....  | 98   |
| 4.16 Concealed washer or plate hub .....                        | 98   |
| 4.17 'Fixed axial angle' tube and channel hub .....             | 99   |
| 4.18 Ditto .....  | 100  |
| 4.19 'Fixed axial angle' plate hub .....                        | 100  |
| 4.20 'Fixed face angle' steel strap .....                       | 101  |
| 4.21 Flexible flat hub .....                                    | 102  |
| 4.22 Ditto .....  | 103  |
| 4.23 Ditto .....  | 104  |
| 4.24 Skinning : setting out triangular panels .....             | 105  |
| 4.25 Hub connection for circular struts - thatch covering ..... | 109  |
| <br><u>Panel Domes</u>  |      |
| 4.26 Timber-framed panels : Strut details : splay-cut .....     | 116  |
| 4.27 Ditto : mitre-cut .....                                    | 117  |
| 4.28 Ditto : bevel-cut .....                                    | 117  |
| 4.29 Ditto : bevel-cut .....                                    | 117  |

|  | Page |
|--|------|
| 4.30 Flanged panels : cross braking .....                      | 119  |
| 4.31 Ditto : joining - bolting or inverted standing seam ..... | 119  |
| 4.32 Ditto : bolting .....                                     | 120  |
| 4.33 Ditto : inverted standing seam .....                      | 120  |

#### Prototype Dome A

|   |     |
|---|-----|
| 5.1 Setting-out .....                             | 139 |
| 5.2 Shuttering alternative .....                  | 141 |
| 5.3 'Standard panel' dimensions .....             | 143 |
| 5.4 Strut drilling details .....                  | 146 |
| 5.5 Correctly manufactured panel .....            | 146 |
| 5.6 Great circle 'bands' of panels .....          | 156 |
| 5.7 Truncated icosahedron .....                   | 157 |
| 5.8 'Closure' panels .....                        | 158 |
| 5.9 Special 'closure' panel at door opening ..... | 158 |
| 5.10 Manufactured 'closure' panels .....          | 159 |
| 5.11 Alternative 'door set' .....                 | 166 |
| 5.12 Alternative hood-panel over door .....       | 166 |
| 5.13 Hinged ventilation panel .....               | 169 |
| (see also List of Working Drawings)               |     |

#### Alternative Geodesic Designs

|  |     |
|--|-----|
| 6.1 Triacanthedron expanded along a 'zone' of parallel edges .....                                   | 179 |
| 6.2 Diamond face of Triacanthedron .....   | 179 |
| 6.3 'Golden diamond' of Icosahedron .....  | 180 |
| 6.4 Relationship between 'golden diamond' of Icosahedron<br>and diamond face of Triacanthedron ..... | 181 |

#### Evaluation of Prototype Dome A

|   |     |
|---|-----|
| 7.1 Solar shading .....   | 187 |
| 7.2 Insulated 'horizontal roof panels'; sand-filled 'vertical'<br>wall panels ..... | 195 |
| 7.3 Interior atmospheric motion .....   | 196 |
| 7.4 Complementary half-hexagons of the truncated Icosahedron .....                  | 203 |
| 7.5 Fusion rings of 3-frequency Icosa-alternate .....                               | 204 |
| 7.6 Fusion between a 5/8-dome and a 3/8-dome .....                                  | 204 |
| 7.7 Fusion between two 5/8-domes .....  | 205 |
| 7.8 Fusion between two 4-frequency Icosa-triacon<br>hemispheric domes .....         | 205 |



|   | Page |
|---|------|
| 7.9 Fusion between Octa-alternate hemispheric dome and structures manifesting 90°, 180° and 270° angles ..... | 206  |
| 7.10 Passage junction between domes .....   | 207  |

### Geodesic Maths

|  |     |
|--|-----|
| B.1 Four closest-packed spheres defining the Tetrahedron .....   | 248 |
| B.2 Frequency of subdivision of edges of one triangular principal facet of Tetrahedron .....                   | 249 |
| B.3 Vector Equilibrium and Icosahedron .....   | 250 |
| B.4 3-frequency subdivision of Vector Equilibrium and Icosahedron .  | 251 |
| B.5 Platonic polyhedra .....   | 252 |
| B.6 Dual polyhedra .....   | 254 |
| B.7 Triacontahedron .....  | 254 |
| B.8 Cuboctahedron, Isidodecahedron, Truncated Icosahedron .....  | 255 |
| B.9 Icosahedron's three unique axes of spin .....  | 256 |
| B.10 Rotation of Icosahedron on an axis through the centre of opposite faces defines ten great circles .....   | 257 |
| B.11 Rotation of Icosahedron on an axis through midpoint of opposite edges defines fifteen great circles ..... | 258 |
| B.12 Rotation of Icosahedron on an axis through opposite vertexes defines six great circles .....              | 258 |
| B.13 One facet of Icosahedron divided by thirty-one great circles ....   | 259 |
| B.14 Derivation of chord factor .....  | 260 |
| B.15 Face angles and central angles .....  | 260 |
| B.16 Face angles and central angles of Icosahedron .....   | 261 |
| B.17 Axial angles .....  | 262 |
| B.18 Dihedral angles .....   | 262 |
| B.19 Face angles of spherical Icosahedron .....  | 263 |
| B.20 Right-angled spherical triangle .....   | 264 |
| B.21 Napier's Rule .....   | 265 |
| B.22 Angles of LCD spherical triangle .....  | 268 |
| B.23 Triacon breakdown : 2-frequency subdivision of an ico-facet ..  | 270 |
| B.24 Triacon breakdown : 4- and 6-frequency subdivision of an ico-facet .....                                  | 271 |
| B.25 Projecting vertexes onto the surface of a circumscribed sphere .  | 271 |
| B.26 Six LCD right-angled triangles of an ico-facet .....  | 272 |
| B.27 Subdividing central angle .....   | 272 |
| B.28 Alternate breakdown .....   | 273 |
| B.29 Alternate breakdown : 3-frequency subdivision of an ico-facet   | 274 |
| B.30 Subdividing central angle .....   | 274 |



|   | Page |
|---|------|
| B.31 Joining points of subdivision .....                                      | 274  |
| B.32 'Windows' around joints of subdivision .....                             | 275  |
| B.33 Triacon breakdown : Hemispheric truncation of Icosahedron .....          | 276  |
| B.34 Diamond face of Triacontahedron divided into four LCD<br>triangles ..... | 277  |

## LIST OF WORKING DRAWINGS

|    |  |     |
|----|--|-----|
| 1  | Perspective views .....                      | 127 |
| 2  | Floor plan .....                             | 128 |
| 3  | Setting out .....                            | 129 |
| 4  | Foundations : formwork details .....         | 130 |
| 5  | Panel manufacturing details .....            | 131 |
| 6  | Assembly details .....                       | 132 |
| 7  | Anchoring the dome to the foundations .....  | 133 |
| 8  | Developed elevation .....                    | 134 |
| 9  | Cross-section and Window-set 1 details ..... | 135 |
| 10 | Window-sets 2, 3, 4 details .....            | 136 |
| 11 | Door-set details .....                       | 137 |
| 12 | Ventilation details .....                    | 138 |

## LIST OF ILLUSTRATIONS

|     |  |    |
|-----|--|----|
| 3.1 | Lion sculpture outside China's Summer palace, illustrating<br>first recorded geodesic dome, 1885 ..... | 68 |
| 3.2 | 'Wonder of Jena' dome, East Germany, 1922 .....  | 68 |
| 3.3 | 4D Dymaxion house, 1928 .....  | 71 |
| 3.4 | Twin Dymaxion Deployment Unit (DDU), 1940-41 .....   | 71 |
| 3.5 | Dymaxion Dwelling Machine (Witchita house), 1944 .....   | 71 |
| 3.6 | 'Ford dome', Dearborn Rotunda building, 1952 .....   | 73 |
| 3.7 | 'Marine Corps Study' dome, 1954 .....  | 73 |
| 3.8 | 'Kleenex' paperboard dome, 1954 .....  | 75 |
| 3.9 | Geodesic Radome, 1955 .....  | 75 |

|   | Page |
|---|------|
| 3.10 U.S. Department of Commerce dome at International Trade Fair, Kabul, Afghanistan, 1956 ..... | 75   |
| 3.11 Kaiser Aluminium Co. dome, Honolulu, Hawaii, 1958 .....                                      | 77   |
| 3.12 Geodesic Plydome, 1957 .....   | 77   |
| 3.13 Burmese toy ball .....   | 77   |
| 3.14 'Indhlu' Geodesic dome, 1958 .....   | 77   |
| 3.15 Union Tank Car Co. dome, Baton Rouge, Louisiana, 1959 .....                                  | 79   |
| 3.16 'Basketry Tensegrity' structure, Southern Illinois University, 1960 .....                    | 79   |
| 3.17 'Geospace' foam-core paperboard dome, 1961 .....   | 79   |
| 3.18 'Peasedome' .....  | 81   |
| 3.19 'Drop City', 1965-1970 .....   | 81   |
| 3.20 'EXPO '67' dome, Montreal .....  | 81   |
| 3.21 Dyna dome .....  | 83   |
| 3.22 Climatron .....  | 83   |
| 3.23 'Temcor' dome, California .....  | 83   |
| 3.24 Richard Buckminster Fuller .....   | 84   |
| <br>  |      |
| 5.1 'Everite dome, Brackenfell .....  | 123  |
| 5.2 'World of Birds' dome, Hout Bay .....   | 124  |
| 5.3 Foundation shutters .....   | 140  |
| 5.4 Panel manufacture .....   | 148  |
| 5.5 Ditto .....   | 148  |
| 5.6 Foundations and sole-plate .....  | 149  |
| 5.7 Ditto and spacers .....   | 151  |
| 5.8 Ditto .....   | 151  |
| 5.9 Reinforced upright base panels .....  | 152  |
| 5.10 Reinforced inverted base panels and some unreinforced 'standard' panels .....                | 153  |
| 5.11 First great circle arch complete .....   | 154  |
| 5.12 Ditto .....  | 154  |
| 5.13 'Standard shell' assembly continued .....  | 155  |
| 5.14 'Standard shell' completed .....   | 155  |
| 5.15 Pentagonal opening ready for windows .....   | 161  |
| 5.16 'A modern indhlu' .....  | 161  |
| 5.17 Window-set No. 3 .....   | 162  |
| 5.18 Window-set No. 4 .....   | 162  |
| 5.19 Window-set No. 3 .....   | 163  |

|  | Page |
|--|------|
| 5.20 Window-set No. 4 .....                | 163  |
| 5.21 Window-set No. 3 .....                | 164  |
| 5.22 Ditto .....                           | 164  |
| 5.23 Special picture window .....          | 165  |
| 5.24 Ditto .....                           | 165  |
| 5.25 Door-set .....                        | 167  |
| 5.26 Ditto .....                           | 167  |
| 5.27 Sealing the dome .....                | 171  |
| 5.28 Ditto .....                           | 171  |
| 5.29 Ditto .....                           | 171  |
| 5.30 The finished dome .....               | 172  |
| 5.31 Ditto .....                           | 172  |
| 5.32 Ditto .....                           | 172  |
| 5.33 Finished Window-set No. 1 .....       | 173  |
| 5.34 Finished Special picture window ..... | 173  |
| 5.35 Finished Window-set No. 4 .....       | 174  |
| 5.36 Ditto .....                           | 174  |

## LIST OF TABLES

|   |     |
|---|-----|
| 1.1 Development of rural shelter in Southern Africa .....   | 14  |
| 2.1.1 Population projections by race : 1980-2015 .....  | 18  |
| 2.1.2 Black incomes : 1980 .....  | 32  |
| 2.1.3 CPI and BER Building cost index : 1975-1984 .....   | 36  |
| 2.2.1 State-subsidised low-income housing catagorisation : 1980 .....   | 42  |
| 2.2.2 Incomes and maximum affordable percentage for housing .....   | 45  |
| 2.2.3 Replacement cost factor : 1982 .....  | 53  |
| 7.1 Effect of radiant heat on various surfaces .....  | 186 |
| 7.2 Cost structure comparison between a conventional building<br>system and a 'rationalised conventional' industrialised<br>building system ..... | 210 |
| B.1 Relationship between various platonic polyhedra .....   | 253 |

## LIST OF SCHEDULES

|       |   |     |
|-------|---|-----|
| 7.1   | Labour schedule : 'manufacture' of one dome-kit .....         | 213 |
| 7.2   | Labour schedule : 'foundation construction' of one dome ..... | 216 |
| 7.3   | Labour schedule : 'superstructure assembly' of one dome ..... | 221 |
| 7.3.3 | Materials schedule .....                                      | 225 |

## LIST OF PROGRAMMES

|      |   |     |
|------|---|-----|
| 7.1  | Manufacture of 10 dome-kits .....         | 214 |
| 7.2A | Foundation construction of 10 domes ..... | 217 |
| 7.2B | Foundation construction of 20 domes ..... | 220 |
| 7.3  | Superstructure assembly of 10 domes ..... | 222 |

## MAPS

|     |   |     |
|-----|---|-----|
| A.1 | Black Homelands in Southern Africa : 1984 ..... | 241 |
|-----|---|-----|

## ABSTRACT

This dissertation studies the viability of one alternative building system as an option to conventional low-income housing. The need for research in this regard has been expressed by various government committees and commissions of inquiry, as well as by the private sector, to be of vital importance in facing the future housing challenge in southern Africa.

The study is largely confined to black housing. The search for a form of shelter which combines traditional black low-technology and innovative Western high-technology in a successful marriage, brings the geodesic dome to light.

The conclusion reached is that in economic, technical and cultural terms, the dome compares favourably with conventional low-income housing. The social acceptance of the structure is a topic of research beyond the scope of this study.

## INTRODUCTION

Technology may be regarded as a mechanism for solving problems . . . a tool to allocate limited resources optimally . . . an attempt to do more with less. Knowledge, experience, and intuition provide man with a springboard to technological development and further knowledge - an infinite regenerative process. Each apprehended and communicated experience is re-employable and creates knowledge, thus adding to the pool of wealth of mankind. Money does not create wealth - wealth is derived from knowledge! Technology is inherently limited to the present state of knowledge. The application of knowledge to solve problems depends on the need at the time, and on the availability of required resources viz. manpower (brain and brawn), materials and money.

Technology feeds on itself - by solving one problem, more problems are usually created. Without this phenomenon, technology would no longer be necessary . . . and mankind would no longer have a purpose, because problem-solving would be redundant. The question thus arises whether the process of applying technology and knowledge to solve problems is regenerative or degenerative. The state of technology may merely be indicative of the extent of the existing problems - technology may therefore be regarded as undesirable, an evil of modern society, a breeder of problems, a futile attempt to do infinitely more with infinitely less. Perhaps the time has come to start doing less with more . . . less

harm with more thought . . . so that knowledge can be reapplied to steer mankind along a long fruitful path of steady progress.

"If an ancestor from long ago visited us today, what would he be more astonished at - the skill of our dentists or the rottenness of our teeth." (1)

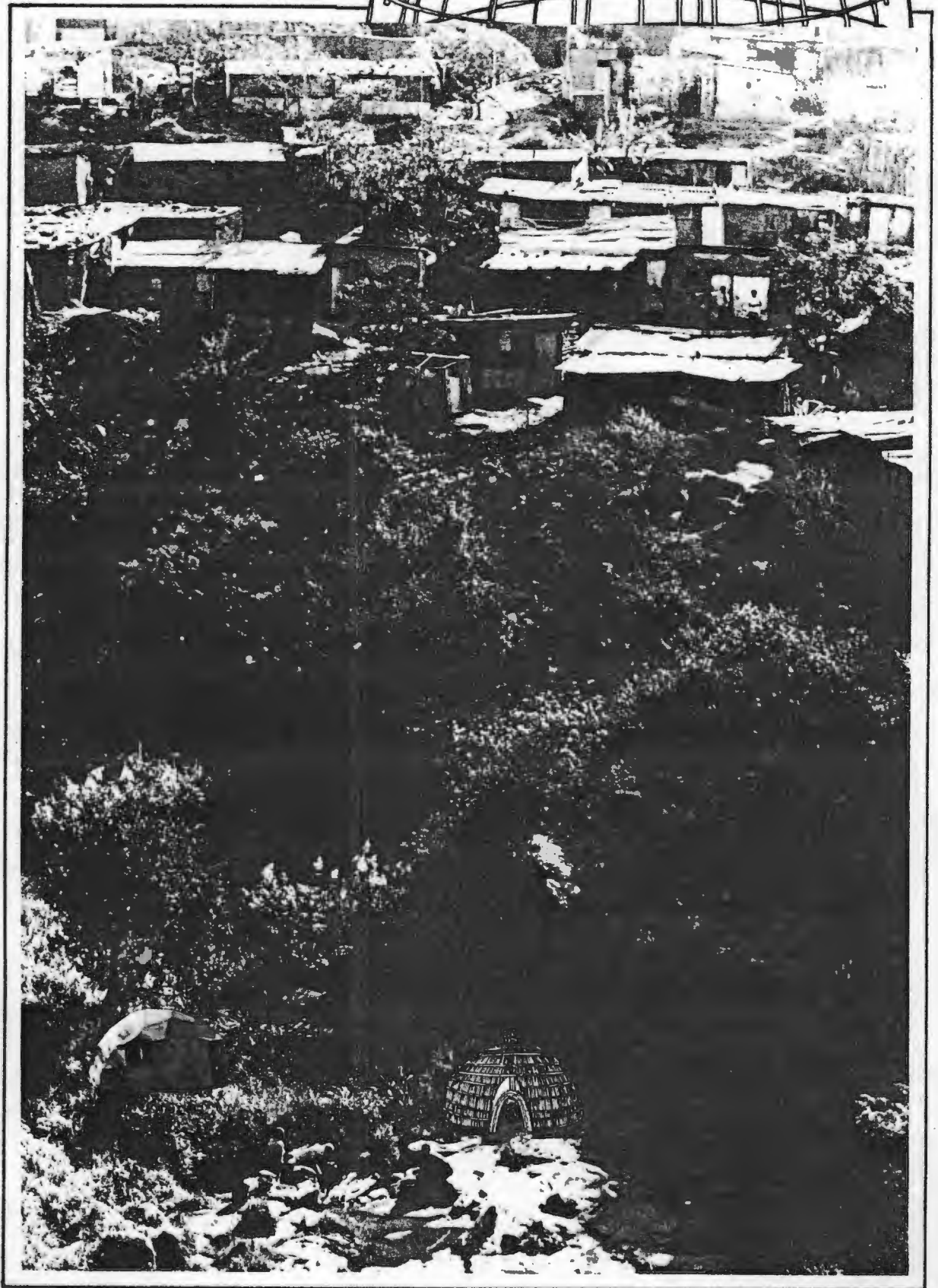
"Perhaps one solution to the world's housing shortage lies in the harnessing of the tremendous energy inherent in rural building. Perhaps the answer does not entirely lie in low technology construction but in a marriage between traditional building methods and an adaptation of modern building materials." (2)

In southern Africa the housing problem is most acutely experienced by the largest sector of the population, the blacks - a race of the Third World, whose traditional well-developed low technology manifests itself strongly in their home - the dome. Western technology - First World space-age technology - is imposed on these relatively 'primitive' people, without intermediary steps of technological development. This sharp interface between two extremely diverse technologies must inherently create confusion and insecurity and, when coupled with high-technology domination and ideological political bias, the problem of adapting to a strange environment becomes awesome. The relentless pursuance of a highly developed Western technology in a country with a labour force largely with low technology skills is absurd - a fairer marriage between technologies may breed more balanced children and a happier nation.

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# SECTION A





## CHAPTER ONE

### 1. TRADITIONAL BLACK AFRICAN SHELTER

#### 1.1 Introduction : Psychology of the Dome

"The dome, ages ago, became symbolic of all the cosmic thoughts, hopes, supplications and glorious conceptions." (1)

The study of traditional black African housing offers an insight into the 'basic needs' and desires of these bantu and the basic nature of the shelter which they built to control their environment.

The essence of traditional architecture is a balanced interaction between man and nature. The indigenous black people of Africa seemed to have had the ability to participate in nature rather than to dominate her, as modern generations are attempting to do. This state of balance between the black man and his environment allowed him to express his subconscious perception of the form of an 'ideal environment'.

"If our grandparents' generation underestimated him, it might well have been because they felt the need to stifle whatever remained of their attachment to the soil, in order to face without regret city life and the uprooting which inevitably resulted." (2)

The image of the black man's house was perceived within a broad environmental cycle of birth, life and death: the womb, the home (dome) and

the tomb. On leaving his mother's womb, man loses his unity with nature and by self-expression he tries to regain that lost unity. Thus the black man enclosed his microcosm with a form emulating his subconscious perception of a place of extreme privacy - his mother's womb, his only previous experience of unity with nature.

"At the largest scale, the all-persuasive influence of the Cosmic Image can be seen in Africa, where in general the sacred is very important, traditional values are not questioned, the symbolic load of artifacts, buildings, and indeed the whole land is very great, and the order of society, the order of thought, and the order of Universe are in close correlation." (3)

Within the cosmic image, the origin of man is expressed by means of a circle, man himself is expressed by means of a square, while the triangle connects man with his origin. Olivier Marc believes that only the young child and primitive man have a sufficiently close affiliation with nature to be able to perceive on a higher plane of consciousness . . . and for both form begins with the circle, because the subconscious initially expresses images of a circular form, which is gradually modified to become a square or a triangle.<sup>4</sup> The circle represents unity and it is the symbol of the perfect and absolute, because from its single centre, man himself, all parts are radially equidistant. The form of shelter which carries this perfection into three-dimensional form, is the hemispheric dome - a microcosm in perfect equilibrium; 'a void containing everything'.<sup>5</sup>

Negro civilisations in Africa originally conceived the circle and the birth of the domical form within this cosmic image. The 'wombhouse' became the physical embodiment of this image. The traditional 'beehive' shelter in southern Africa is either in the form of a dome or a cone. The cone, with its apex pointing towards the heavenly sky, combines the circle with

the triangle expressing an attempt to reach 'the original earthly paradise'  
 - a circle which brings down heaven's blessings.

"The original earthly paradise is always represented by a circle recalling the mother's womb." (6)

"For the Hottentots the circle is the perfect form which brings down heaven's blessings. The huts are round and arranged in a circle around the circular cattle ground." (7)

The door of the house usually assumes a sacred character and is suitably decorated - 'to go through the door is to pass from one place to another'.<sup>8</sup> Painted door surrounds or elaborately woven surrounds indicate the importance attached to the entrance.

"What could be more normal than to decorate and honour the aperture leading into a womb-like world which man first conceived inside his mother's womb. To leave the womb is a natural step, but to enter, or re-enter, is a hope forever doomed to frustration except on a higher plane of consciousness." (9)

The individual self-expression of an 'ideal environment' is perceived within a broader cultural context. Traditionally blacks operated in groups - individuality existed only in character, but cultural practices were shared by a large number of people. Their buildings and settlement patterns were the visible expression of the relative importance they attached to various aspects of life and how they perceived reality. In analysing the house form adopted by these groups one must therefore consider the socio-cultural factors affecting their housing needs - however a detailed analysis thereof is beyond the scope of this study.

"One must find the 'flavour' of a culture's true meaning and beliefs before one can understand its houses." (10)

"All cultures make a selection of their cultural institutions, and 'each from the point of view of another ignores fundamentals and exploits irrelevancies' . . . Through seeing other ways of doing things, we are made aware that there are other ways, that our way may be peculiar rather than inevitable and that our values are neither the only ones, nor the norm." (11)

## 1.2 Classification of Traditional African Shelter

The task of defining distinctly separate classes of black technologies has been attempted by various anthropologists, historians, architects and others, with scriptures referring as far back as the Early Iron Age.<sup>12</sup>

"Radio-carbon dating has provided evidence of negroid iron age settlements in the trans-Vaal as early as the fifth century A.D." (13)

Since those early days the indigenous blacks have roamed across southern Africa, expressing their mode of existence by the form of the artifacts they produced and by the form of their shelter.

"Built form is the physical embodiment of the behaviour patterns of man." (14)

Traditional construction methods vary from region to region and from one tribe to another. Socio-cultural norms and beliefs of various tribes determined their basic housing needs. The geographical location of settlement, related climatic conditions and availability of local material, were the physical factors which merely determined the parameters within which culturally-established housing needs could be best satisfied.

"Nature prepares the site and man organises it to enable him to satisfy his desires and needs." (15)

In southern Africa two predominant black technologies emerged, based on broad cultural affiliation, areas and patterns of settlement, and forms of house construction.

- The Nguni-speakers, who settled in the coastal areas of southern Africa and specialised in reed and thatch construction.
- The Sotho-Tswana-speakers, who inhabited the drier highveld regions and practised mainly wattle-and-daub construction or masonry construction.

(See Appendix A)

#### 1.2.1 The 'beehive dome of the Nguni

The basic theme of Nguni shelter is the 'beehive' dome, a hemispheric form of shelter with no distinction between separate wall- and roof- elements. Having settled in areas of heavy rainfall between the escarpment of the Drakensberg mountain range and the coast, they were provided with ample vegetation for construction. Saplings and grasses inherently lend themselves to the processes of bending, tying and weaving resulting in structures without sharp corners, usually being roughly hemispheric in shape.

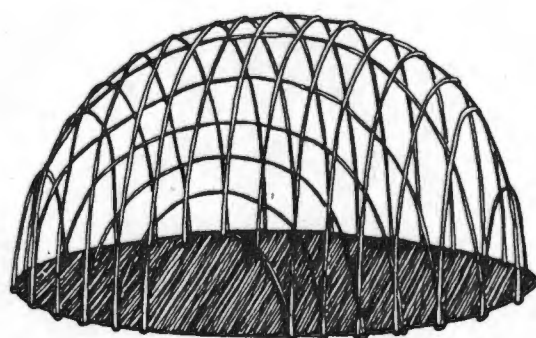
The Nguni-speakers are extremely proficient in the craft of thatching. The extent of Nguni specialisation is clearly evident amongst the Zulu, who use seven different types of grasses each serving a particular function to produce a masterpiece of environmental control.

The 'Indhlu', as the Zulu dome is called, is constructed entirely of vegetation with no windows and only one entrance door. Due to the mystical connotations attached to the entrance, door surrounds are decoratively

dyed, tied and woven and often 'burgeon into lace-like porticos'.<sup>16</sup>

The structural framework of the Indhlu consists of flexible reed saplings planted into the ground at two diagrammatically opposite points on a circular plan. The first set of framing elements is bent in arches, with a great circle arch at the diameter of the circle, and progressively smaller arches extending at regular intervals on either side of the great arch. The second set of saplings is arched over at right angles to the first set, but may be more closely spaced, since members are usually lighter. At each point of intersection the saplings are tied together with woven ropes, creating a perfectly self-stabilising two-way grid hemispheric framework.

Figure 1.1 'Indhlu' Dome Framework (Frescura)

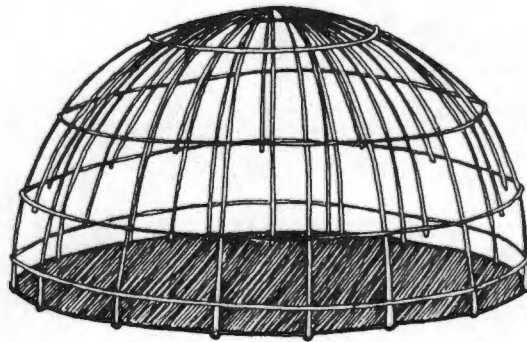


The structure of the Swazi (or Dlamini Ngwane) beehive does not vary substantially from that of the Zulu, except that the second set of reed saplings, set at right angles to the first, is not as closely spaced as in its Zulu counterpart.<sup>17</sup>

The Xhosa beehive framework seems to be derived from that of the Hottentots, with saplings planted into the ground at one end only, on a circular plan. Each sapling is brought radially to a central apex, defining half a great circle arch; at the apex the saplings are tied together. Bracing is provided by horizontal hoops of diminishing size advancing up-

wards towards the apex at increasing intervals. Points of intersection are tied together to form a stable two-way grid 'rectilinear' hemispheric dome framework. Saplings are usually allowed to extend beyond the apex as far as the second or third hoop.

Figure 1.2 : Xhosa Dome Framework (Frescura)

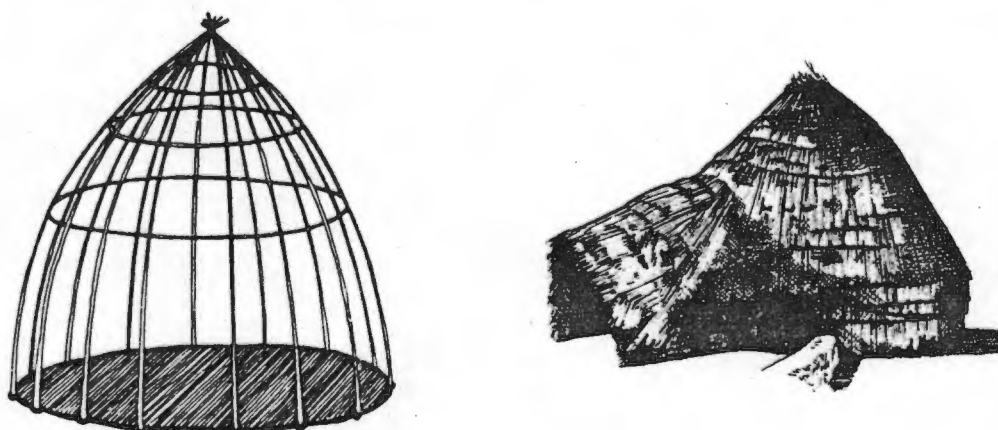


At present the traditional domed grass huts of the Nguni-speakers is almost an extinct architecture. However a tremendous attempt to conserve the first-hand records of traditional Zulu architecture is being made by film-maker Elmo de Wit, under whose auspices authentic traditional huts are being built on the site of Dingaan's immense kraal at Umgungundlovu. The site belongs to the National Monuments Council and has been accepted by the Natal Provincial Museum Services as a provincial museum. The reconstruction of more than 100 hectares of the original site will become a permanent monument with perfect replicas of the 'beehive' dome, some of which will be erected on the excavated floors of the 'isigodlo', the women's quarters of the royal enclosure. Thus the beehive will live on and first-hand recollection of Nguni architecture will be at hand for future generations.<sup>18</sup>

### 1.2.2 The 'Sparrow-pot' Cone of the Sotho

The traditional shelter of the Sotho-speakers consists of a wattle sapling framework, with each sapling planted into the ground at regular intervals on a circular plan. Framing elements are brought radially to a central crown where they are tied. Horizontal hoops of diminishing diameter brace the framework and complete the 'rectilinear' conic-hemispheric two-way grid. The doorway of the hut projects beyond the surface of the cone, forming an entrance portico which gives the structure a 'sparrow-pot' appearance.

Figure 1.3 : 'Sparrow-pot' Cone Framework (Frescura)



A masonry wall is usually built around the outside of the base before the complete structure is thatched. Although the 'sparrow-pot' is the most basic form of traditional Sotho shelter, it was soon superseded by the 'rondavel' type of structure in which the conic roof is supported by a clearly identifiable cylindrical wall. The bright sun, extremes of temperature and relatively low rainfall on the temperate and semi-desert highveld meant that solid walls were necessary to control the temperature inside the dwelling without fear of rainwater eroding the base of walls. In addition, a lack of vegetation, an abundance of clayey soil and an advanced



technology in stone construction inherently promoted the development of wall construction. Walls were painted white to reflect the bright sun and the conic roof projected beyond the wall to form an eaves and a verandah, thus shielding the dwelling from the harsh summer sun. Solid walls efficiently conserve heat in winter and allow for elaborately painted door surrounds.

### 1.3 The Development of House Form

Due to technological advancement and cross-cultural contamination, traditional construction techniques became increasingly bastardised over time. Although traditional housing is inherently non-chronological in nature, there were two major stages of transitional development which modified basic housing needs and clearly affected the traditional house form of southern Africa's indigenous people.

- About 1500 A.D., when the nomadic African herdsmen changed to a semi-sedentary way of life and required a more permanent form of shelter.
- About 1900 A.D., when a sedentary existence became the norm and the influence of European technology became distinctly evident.

It has been suggested that the development of house form may be broadly classified in terms of the importance of the wall as a distinctly separate structural element from the roof.

"Cipriani suggests that as the mode of life changes from hunting to sedentary farming the house-type changes from a spherical shape to a differentiation between the wall and the roof. He therefore implies that the construction of a wall is an important milestone in the development of housing." (19)

This proposition must however to be seen within the context of tribal tradition, and geographical location of settlement. It is clearly evident that the Sotho-Tswana-speakers developed the wall as a separate structural element long before the Nguni-speakers, not because they were technologically more advanced, but for reasons previously explained. However the following broad classification does suggest a chronological development of house form in terms of the importance of the wall as a separate structural element.

- The 'beehive dome, with no distinction between wall and roof.
- Dome - or cone - on minor cylinder, with the wall emerging as a separate and identifiable structural element, but being secondary to the roof.
- Dome - or cone - on major cylinder, with the wall assuming equal structural status to the roof.
- The 'Highveld house', with the wall becoming the major structural element and the roof secondary.

Within these broad groupings there are an almost unlimited number of permutations, depending largely on the method of wall construction, the type of roof structure and roof finish. A handbook in this regard is Franco Frescura's "Rural Shelter in Southern Africa" (see Bibliography).

Table 1.1 shows the broad chronological development of rural shelter in southern Africa in terms of the form of structure on plan, the consequent shape and design of the roof and related problems in construction.

Table 1.1

|   | Shape on Plan | Roof Construction                                   | Roof Finish     | General Remarks  |
|---|---------------|---|-----------------|--|
| 1 | Circular      | Dome/Cone   | Thatch          | No walls   |
| 2 | Circular      | Dome/Cone on Minor/Major Cylinder : 'Rondavel'      | Thatch          | Minor cylinder : up to 1,4 m high<br>Major cylinder : up to 2,1 m high<br>With eaves and verandah      |
| 3 | Square        | Pyramid-shaped, with Hips                           | Thatch          | Problems with waterproofing at apex and along hips   |
| 4 | Rectangular   | Four Hips   | Thatch          | Ridge adds further waterproofing problems  |
| 5 | L-, U-shaped  | Hips, Ridge and Valleys                             | Thatch          | Valleys ditto  |
| 6 | Rectangular   | Ridge and Gable walls, with Verges or Parapet walls | Thatch          | Parapet wall introduces flashing problems  |
| 7 | Rectangular   | Lean-to roof with Parapet walls                     | I.B.R.          | Introduction of non-traditional roof covering solves flashing problems                                 |
| 8 | Hybrid shapes | Various   | I.B.R.<br>F.R.C | Strong European influence; rapid technological development. Traditional architecture no longer evident |

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## CHAPTER TWO

### 2. LOW INCOME HOUSING POLICY IN SOUTH AFRICA

#### 2.1 Defining the 'Housing Problem' : Population Growth, Urban Growth, Poverty

##### 2.1.1 Introduction

Recently much has been said and written about the 'housing problem' in South Africa; however not much action to back-up these words has occurred, as it seems that the problem is worsening and that a solution is becoming more difficult to find as time goes on. Various commissions of inquiry, committees, congresses, conferences and seminars have dealt with assessing the extent of the problem. Exact statistics on housing needs are often quoted, especially of the lower income groups. Although these exactitudes are viewed with reservation, being open to speculation and personal bias of individual researchers, there undoubtedly exists an enormous housing backlog, and future housing demands can clearly not be met by conventional means. The problem revolves mainly around the vast black population which presently constitutes over 70 per cent of the total population south of the Limpopo river. This sector of the population is largely extremely unskilled and discriminated against by the ideological political bias of government policy. In broad terms the problem is one of numbers and poverty.

### 2.1.2 Population Growth

Demographics entails the study of population growth and an analysis of the composition of the total population in terms of race, age and sex, with the aim of determining dependency ratios, training - and job requirements, as well as housing needs. Economic forecasts, based on projected demographic trends, must be extrapolated from accurate statistical records. In South Africa, population statistics are open to much speculation and prone to reflect personal assumptions of various researchers. The 1980 census, of which only three reports, based on a mere 5 per cent sample, have been published, is of limited value to demographers and business planners at this stage. Exact statistics as regards the black population are especially viewed with extreme reservation for the following reasons:

- The success rate of the homeland development policy is often disregarded and, if taken into consideration, estimates are usually based on biased views and assumptions.
- Quoted estimates do not always specify whether they are confined to blacks in white areas or to homeland blacks, or whether the total black population is implied. Assumptions as regards the number and designation of migrant workers are also often confusing.
- Akin to the above, the Central Statistical Services in Pretoria ceases to publish statistics pertaining to Black States when they are granted political independence - since 1976, official statistics have thus been subject to political developments in South Africa.
- The lack of distinction between urban and rural blacks often creates distorted views.

For the purpose of the following brief study, statistics include the population of all the homelands unless otherwise stated.

Independent Homelands: Transkei (1976)  
Bophuthatswana (1977)  
Venda (1979)  
Ciskei (1980)

Non-independent Homelands: Gazankulu  
Kangwane  
Kwandebele  
Kwazulu  
Lebowa  
Qwa Qwa

(See Appendix A : Map A)

Table 2.1.1 Population Projections by Race: 1980-2015

|      | Whites    | Coloureds | Asians    | Blacks     | Total      |
|------|-----------|-----------|-----------|------------|------------|
| 1980 | 4 528 100 | 2 612 870 | 821 320   | 20 628 900 | 28 591 190 |
| 1985 | 4 801 012 | 2 843 278 | 899 453   | 23 623 300 | 32 167 043 |
| 1990 | 5 035 340 | 3 086 231 | 972 207   | 27 066 800 | 36 160 578 |
| 1995 | 5 256 045 | 3 319 557 | 1 040 158 | 30 766 000 | 40 381 760 |
| 2000 | 5 467 312 | 3 523 221 | 1 101 520 | 34 770 700 | 44 862 753 |
| 2005 | 5 655 908 | 3 692 312 | 1 151 543 | 39 060 800 | 49 560 563 |
| 2010 | 5 815 004 | 3 830 007 | 1 199 312 | 43 547 200 | 54 391 523 |
| 2015 | 5 943 354 | 3 966 846 | 1 242 207 | 48 155 500 | 59 307 907 |

Source: Grobbelaar, J.A., Projections and Analysis of the South African Population for the period 1980-2015, UFR, University of Stellenbosch, 1983, p. 76.

In 1980 the total population of 'South Africa' constituted 28,6 million persons, of which 72,2 per cent (20,6 million) were blacks, who were almost equally divided between homeland blacks, representing approximately 10,7 million persons,<sup>1</sup> including approximately 1,5 million migrant

workers, and blacks in white areas, representing almost 10,0 million persons. In 1975 the respective figures were 8,8 million and 9,2 million.<sup>2</sup> Thus over the five-year period 1975-1980 the homeland population increased by 21,6 per cent, while the number of blacks in white areas rose by only 8,7 per cent. However the high percentage increase in the homelands does not necessarily mean that blacks are flooding back from white cities. It is indicative, more probably, of children born to the wives of city breadwinners who visit their families once a year.

It is forecast that the black population in white areas will increase at an average annual rate of 2,5 per cent to the year 2015,<sup>3</sup> while the homeland population is expected to grow at an average annual rate of 2,7 per cent,<sup>4</sup> as compared to an average annual growth rate of 1,2 per cent for coloureds and Asians and 0,8 per cent for whites.<sup>5</sup> Thus by the turn of the century 77,7 per cent of the total population will be blacks, representing 34,8 million persons; by the year 2015 the estimated 48,2 million blacks will constitute 81,2 per cent of the total population. Although these growth rates are alarmingly high, it is predicted that the rate of increase will decline - 2,76 per cent annually during the eighties, 2,63 per cent in the nineties and 2,17 per cent from the turn of the century to the year 2015.<sup>6</sup> This encouraging expected trend has been based on the assumption (and on recent evidence) that black families have realised that white-induced birth-control measures are not merely politically motivated, but of vital economic and social consequence.

In its 1983 Survey, the South African Institute of Race Relations quotes the Science Committee of the President's Council, stating that 'in order to avoid a "disastrous and uncontrollable" population explosion in South Africa, steps should be taken to stabilise the population growth by the



year 2020. If by the year 2000 every woman in South Africa could be persuaded to have only two children, by 2150 the population would have stabilised at about 62 million. If every woman had three children by 2000, the total population in 2150 would be 450 million - and would still continue to grow.<sup>7</sup> In its report on demographic trends the Committee suggests a 43-point plan for the implementation of an effective population control strategy aiming at a stable population of 80 million persons by the end of next century.

Projections of the racial composition of the South African population, briefly outlined above, must be analysed in conjunction with the age composition of the population. Fertility rates and mortality rates are both forecast to decrease in the future.<sup>8</sup> The annual growth rate of black infants and youths (0-14 age group) is thus expected to decrease, whereas that of the aged (65+ age group) will increase. The 15-64 age group is forecast to increase at a faster rate than the other age groups,<sup>9</sup> largely due to the relatively high fertility rate of blacks over the last two decades and due to an expected decrease in future mortality rates. Thus the demand for new job opportunities and for secondary- and tertiary-training facilities is now increasing more rapidly than present total population growth rates would imply. Unfortunately this potential new increment to the labour force is relatively unskilled, since, as dependents, they were not granted the privilege of an adequate primary education.

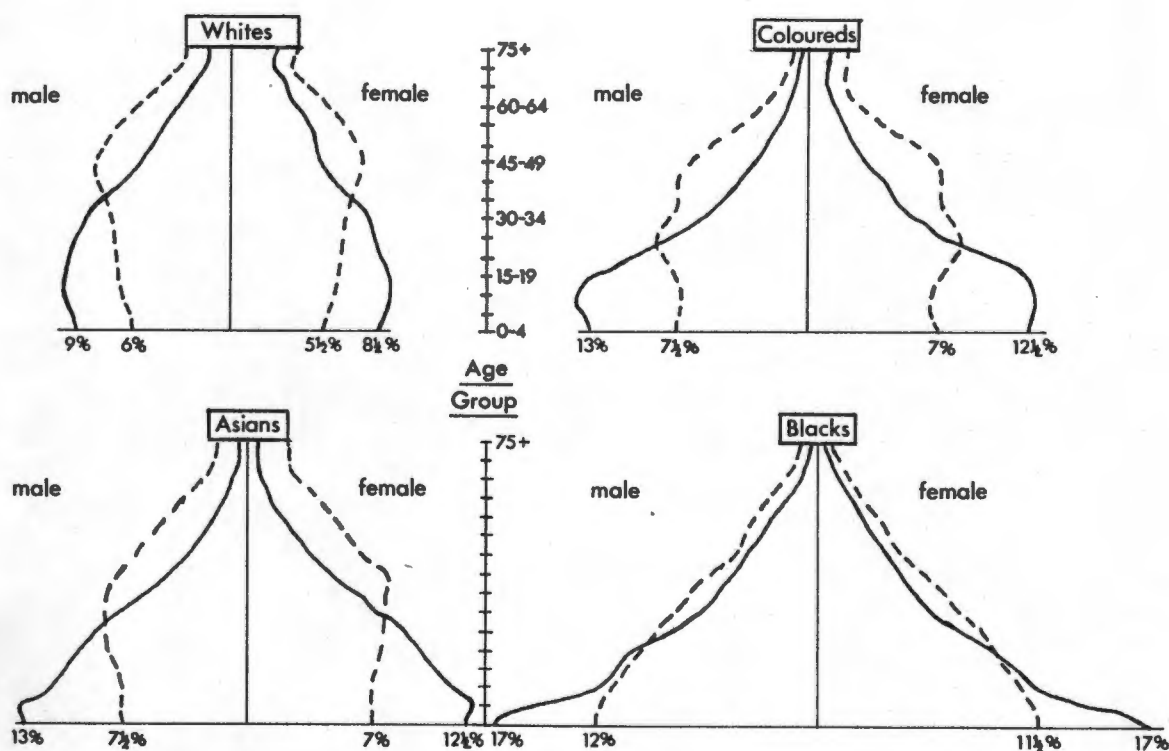
Due to decreasing fertility rates, the number of black household heads is expected to increase by 86 per cent over the period 1980-2000;<sup>10</sup> thus families are predicted to become smaller, thereby increasing the demand for dwelling units at a faster rate than would be predicted from given increases in population (see 2.1.3.1).

In 1980 the age composition of each race group portrayed the classic 'pyramid' structure, indicating high dependency ratios, especially amongst the black population. Graphs 2.1.1 (A-D) show that by the year 2015, dependency ratios will be lower than in 1980 - there are relatively more economically active people as the graph becomes more 'bulge' shaped. Black dependency ratios are still predicted to be the highest, and by the year 2015 it is expected that the black population will reach that stage of the demographic cycle as the white population in 1970 and coloureds and Asians in 1980.

Graphs 2.1.1 (A-D) Age Composition by Race

— in 1980

- - - - in 2015



Source: Grobbelaar, J.A., INTERCOM newsletter, Marketing Services Department, Rightford, Searle-Tripp and Makin, July 1983, p.4

### 2.1.3 Urban Growth

"From now to the turn of the century, the urbanisation of the black people is and will remain the single most important factor in the South African environment." (11)

In 1980 approximately one-third of the total black population was urbanised, representing 6,8 million persons.<sup>12</sup> Of the 10,0 million blacks living in the Republic of South Africa, 5,3 million (or 53 per cent) were urbanised, while only 1,5 million (or 14 per cent) of the homeland blacks resided in urban areas.<sup>13</sup> The population of Ciskei and Kwazulu are by far the most urbanised of all homelands, representing 67 per cent of the total homeland urban population or 1 million persons in 1980.<sup>14</sup> Although 35,8 per cent of the Ciskei population and only 22,1 per cent of the Kwazulu population was urbanised in 1980, in absolute numbers, the Kwazulu urban population constituted more than 50 percent of the total homeland urban population, representing approximately 750 000 persons.

By the year 2000, the level of black urbanisation is officially expected to reach 75 per cent, representing approximately 26 million persons. However the first Venter report on 'Township Establishment and Related Matters' (April 1984) states that this target is difficult to support and forecasts that by the turn of the century only a 50 per cent level of black urbanisation is possible,<sup>15</sup> representing an estimated 17 million persons. Predictions as regards the level of black urbanisation by the year 2000 depend largely on various researchers' assumptions of the success rate of the decentralisation policy and the homeland development policy. The Unit for Futures Research predicts a 60 per cent black urbanisation level by the turn of the century,<sup>16</sup> a forecast based on the assumption that the future decentralisation of economic development might absorb the pre-

sent homeland population and its increment, but that all other future population growth will settle on the periphery of the present metropolitan areas. For the period 1980-2000 the UFR predicts a 228 per cent increase in black urbanisation from 6,4 million to 20,9 million persons.<sup>17</sup> Assuming that at least 50 per cent of this urban population will be absorbed by homeland urban centres, the black population in white urban areas will almost double by the year 2000. The homelands are faced with even more daunting statistics and a 700 per cent increase in urbanisation, from 1,5 million persons in 1980 to 10,5 million by the year 2000, is highly unlikely.

The centralisation of urban growth points in four major white metropolitan areas – P W V region, Durban – Pinetown, Port Elizabeth – Uitenhage and the Cape Peninsula – seems to be economically, socially and politically undesirable. Although these centres are the optimal locations from the point of view of profit-making private industry, the fact that 65 per cent of the total black urban population or 45 per cent of the total black population in white South Africa, representing almost 4,4 million persons,<sup>18</sup> has settled on only 4 per cent of the land surface of South Africa, induces hidden costs in the provision of additional services, such as water- and power- supply, sanitation, transport, health- and recreational- facilities, housing, and in the maintenance of law and order. However this urbanisation process, being an inevitable consequence of economic, social and technological development of a modern industrial-based economy, cannot be prevented by mere legislation based on political ideologies – the pace and pattern of urbanisation can however be fundamentally adjusted by government policy. Over the past two decades it has been official government policy in South Africa to strictly control the influx of black work-seekers to white urban areas by legislation under section 10

of the Urban Areas Act, amongst others, while at the same time promoting the development of decentralised growth points mainly in white border areas on the periphery of the black homelands. However despite special inducements in the form of tax remissions, capital assistance for the erection of factories, concessions as regards railway freight rates and exemption from minimum wage determinations, offered to industrialists who wish to establish factories in decentralised locations to offset any initial locational disadvantage, the pace of industrial development has been far too slow to provide sufficient job opportunities for the rapidly growing labour force. Thus, for economic reasons, the policy of influx control cannot prevent increasing black urbanisation rates in - and around - the main white centres, until the opportunity of finding a livelihood in decentralised locations exists. In addition, a basic infrastructure of utilities, social amenities and accommodation must underlie the development of self-sufficient, economically - and socially - stable communities. The decentralisation policy in South Africa has also been associated with the government's controversial 'apartheid' policy and it is thus emotionally and politically charged.

In 1982 the National Manpower Commission reported that 93,1 per cent of the economically active population in 1980 was employed in white South Africa (of which 31,3 per cent worked in the P W V area) and only 6,9 per cent in the black homelands.<sup>19</sup> The Viljoen report (1981) states that in 1980 35,7 per cent of the population of South Africa was resident in the homelands, which produced only 3,4 per cent of South Africa's GDP.<sup>20</sup> Such statistics clearly indicate the extremely slow rate of industrial development in the homelands. In 1980 the total economically active population in South Africa (including all black homelands) was approximately 9,5 million persons, of which 6,3 million were blacks.<sup>21</sup> The National Man-

power Commission estimates that by the year 2000 there will be 10,7 million economically active blacks, an increase of 70 per cent over twenty years. The creation of sufficient job opportunities, especially by rapid industrial expansion in the homelands, is thus of utmost economic, social and political importance, so that unemployment is kept down to an acceptable level (see 2.2.3.1).

"For every R1 million invested in low-income housing, between 250 and 500 man years of employment are created (depending on the housing method employed - self-help schemes generating more employment)." (22)

In conclusion it must be stressed that the problem of urban growth in South Africa has recently been exacerbated by one of the country's worst droughts in history, which is driving masses of rural people to the cities.

In view of the fact that urban growth, especially of the major centres in white South Africa, will inevitably occur in the foreseeable future, it is now more important than ever that a realistic urban policy is formulated to develop decentralised growth points into operational working urban systems. In formulating such an urban policy it must be taken into account that the process of urbanisation in South Africa is basically a sharp, direct, immediate interface between the Third - and First - Worlds. A successful urban policy must therefore be tailored to suit this interface - high ranking priorities for such a policy must include education and training, the provision of work opportunities, transport systems and housing.

"I think the pace at which change is taking place, which is caused by technology feeding on itself in the advanced countries, is the fundamental cause of all our urban problems . . ." (23)

Professor E.W.N. Mallows emphasises that rapid urbanisation is certainly

not merely a South African phenomenon. She believes that as a direct result of rapid urbanisation the world will undergo radical social, economic and political changes within the next decade or two. Super-cities such as Tokyo which, with all its suburbs, may be the centre of an urban area of 80 million people by the year 2000, must create entirely new problems in human relationships amongst each other and with the environment as a whole.

#### 2.1.4 Poverty

Financial ability is the single most important factor in determining the demand for housing. Every budget, whether on a national or an individual level, has funds allocated to the provision of accommodation. The proportion spent on housing in relation to other items in the budget depends on affordability and on relative priorities. The question which underlies the following brief analysis is whether firstly the State, and secondly the individual home-seeking family, can afford the financial burden imposed by the present low-income housing policy.

##### 2.1.4.1 National Affordability

In the national interest a solution to the housing problem in South Africa must rank very high. Besides defence and education, housing is the first priority and capital invested for this purpose should be regarded as 'soft-defence' expenditure or as current expenditure which is not capitalised.

The low-income housing policy in South Africa is characterised by extensive State subsidisation (see 2.2). Private sector involvement in the provision of low-income housing has in the past been minimal because the operation of an open market system has been undermined by the ineffi-



cient system of subsidisation. Strict State control over minimum housing standards has led to the incongruous situation where neither the private - nor the public - sector can muster the required expenditure, and individuals who are attempting to cut the coat according to the cloth available are becoming disillusioned as the opportunity of facing the challenge ahead with any hope of success is diminishing exponentially with time.

If the present policy is pursued, with the public sector providing approximately 90 per cent of all black housing outside the homelands, 80 per cent of all coloured housing, 65 per cent of all Asian housing and 15 per cent of all white housing,<sup>24</sup> the required annual State capital expenditure is R2 600 million (at 1982 prices),<sup>25</sup> almost four times the investment in residential buildings by the public sector in 1982.<sup>26</sup>

In 1978 the total investment in residential buildings in South Africa constituted 2,5 per cent of GDP (at market prices), as compared to 4,2 per cent in 1970.<sup>27</sup> However Reserve Bank statistics show that since 1978 this trend has been reversed and by 1983 investment in residential buildings had risen to 3,8 per cent of GDP,<sup>28</sup> an increase possibly largely attributable to the extremely rapid rate of increase in building costs from 1979 to 1982 (see 2.1.3.2.2). Dr. Robin Lee, Managing Director - and Director of Planning and Development - of the Urban Foundation, recently quoted the Prime Minister's Planning Section in predicting that 2,5 million housing units are required in urban areas of South Africa from 1982 to 1990, or on average an annual demand of 310 000 units, at an estimated cost (at 1982 prices) of almost R4 000 million for conventional housing. This required investment amounts to approximately 6 per cent of the country's GDP in 1981.<sup>29</sup>

Mr. D. Mullins, Senior Planner in the Department of Constitutional



Development and Planning, estimates that 2,3 million housing units are required for the nine-year period 1982-1990 to wipe out the present housing backlog and to keep up with the expected population growth. Of these required units, 1,8 million are for black housing, representing a required annual investment of approximately R2 300 million by the public sector alone (at 1982 prices).<sup>30</sup>

Mr. J.A. Grobbelaar, Senior Economist at the Unit for Futures Research (UFR) at the University of Stellenbosch, is more conservative in estimating the extent of future housing requirements. Assuming there to have been no housing backlog in 1980, he estimates that over the period 1980 to 1990 approximately 1,23 million dwelling units are needed to keep up with the expected population growth, of which almost 1 million units are required by black families.<sup>31</sup> Assuming the present backlog of black housing to be approximately 500 000 units,<sup>32</sup> the average annual demand to wipe out the backlog and to keep up with expected population growth is 150 000 units for the period 1980-1990. Mr. Grobbelaar estimates that for the period 1990-2000, 1,80 million dwelling units are required to house the increment of the total population, of which 1,23 million units are for black families.

In forecasting future housing demands careful note must be taken of the expected size of an average family. At present the average black family is presumed to consist of 6 to 6,5 persons. If the latter is assumed, as Mr. Grobbelaar does, the required number of housing units would inherently be almost 8 per cent less than for 6-person families. In view of the fact that black families are expected to become smaller in the near future (see 2.1.2) the extent of future housing needs could be even greater than has been predicted.

The first Venter report (April 1984) states that R87 500 million is required over the next 16 years (1984-2000) to provide sufficient accommodation by conventional means in urban areas of South Africa, an average annual demand of almost R5 500 million (at 1983 prices),<sup>33</sup> as compared to the 1983 investment in residential buildings of R3 336 million.<sup>34</sup> The major portion of the shortfall of funds is assumed to be for black housing.

In 1982 Dr. Piet Koornhof, Minister of Co-operation and Development, estimated the total backlog of black housing in urban areas of South Africa to have been 168 000 units.<sup>35</sup> while the annual demand is 35 000 units.<sup>36</sup> At a supply of 20 418 units in 1982<sup>37</sup> (13 523 units by the public sector and 6 895 units by the private sector), the backlog is increasing by almost 16 000 units annually. This clearly indicates the exponential growth of the gap between demand and supply, resulting in an ever - increasing housing backlog.

The housing shortage in the homelands (independent and non-independent) is even greater than in black urban areas of South Africa. At the end of 1982 the backlog was estimated to have been 230 000 units<sup>38</sup> and Dr. Koornhof estimated that between 300 000 and 500 000 dwelling units were required over the next five years in the non-independent homelands alone, approximately ten times as many as were provided by the State in the twelve-year period 1971-1983.

Although exact estimates vary slightly from one source to another, the extent of the shortfall of public funds is clearly evident from the brief foregoing analysis. Thus private sector involvement in black housing and a lowering of minimum housing standards are pre-requisites to a successful attempt at solving the low-income black housing problem in South Africa.

"Dr. George de V. Morrison, Deputy Minister of Co-operation, said that the government could simply not afford to supply Africans with housing. 'The sweat capital of the African must come into question', he said, 'and Africans should provide their own housing.'" (39)

"A reduction in housing standards is inevitable in the light of the country's limited resources, and alternative methods of house building, especially if less expensive, are likely to be increasingly used. There is likely to be growing 'do-it-yourself' or 'self-help' input." (40)

#### 2.1.4.2 Individual Affordability

"In a market economy, needs are fulfilled according to financial ability, not according to urgency. Or in traditional economist's terms, supply is provided according to effective demand." (41)

The effective demand for housing represents what individual families are able and willing to pay for their accommodation. The level of household incomes and the distribution thereof, as well as the prices of available housing and of other goods and services, are important influences on decisions about how much to spend on housing in relation to other items on the household budget. In order to determine effective demand at prevailing costs and incomes, the widest possible range of housing options should be defined and the economic cost (or rental value) of each system should be accurately established. Thus real costs must be carefully evaluated, not 'apparent' costs, induced by present State-subsidisation, and housing standards must be lowered to a point where individual families can effectively afford their accommodation.

"The demand is for a wide range of housing options of differing standards, degrees of completeness and design." (42)

The two major factors influencing a family's financial ability to house itself are:

- (a) Income
- (b) Housing costs

#### 2.1.4.2.1 Black Incomes

The income earning capacity of the vast majority of blacks is extremely low. However exact figures given by various researchers and statistical information sources vary substantially due largely to the following factors:

- It was previously stated (see 2.1.2) that since 1976 demographic statistics of the black population have been subject to political developments in South Africa and that the Central Statistical Services in Pretoria ceases to publish statistics pertaining to black homelands when they become politically independent. Thus statistics as regards employment, wages and salaries must be carefully adjusted when making comparative studies.
- The difference between wages and salaries and 'real' incomes are often disregarded in affordability calculations.
- Statistics do not always cover all employees in the South African economy. Agricultural workers and domestic servants are sometimes omitted from official statistics. In addition, it seems unclear whether unemployed people should be regarded as economically or non-economically active persons.
- The greatest problem is that secondary data is often misinterpreted, because sources often make implicit assumptions - thus statistics can be exploited to suit the personal bias of various researchers.

The second Carnegie Inquiry into Poverty and Development recently out-

lined the extent of the poverty which exists amongst the black population. In June 1984, the leader of the Opposition in South Africa, Dr. van Zyl Slabbert, reported in Parliament that although the proportion of homeland blacks living below the Poverty Datum Line (PDL) had decreased from 99 per cent in 1960 to 81 per cent in 1980, the number of people in absolute terms, living below the PDL had more than doubled from 4,1 million to 8,91 million.<sup>43</sup>

In March 1983, Mr. J. Kruger, National Housing Manager of the Urban Foundation, quoted figures compiled by DORIDA Management Services (see Table 2.1.2) which show that more than 70 per cent of all black families in South Africa live below the average Household Subsistence Level (HSL), which for a black family of six persons was approximately R270 per month at September 1983.<sup>44</sup>

Table 2.1.2 Black Incomes: 1980 (net incomes assumed)

| Monthly Income<br>(in R) | Percentage of Black Population<br>(in %) |          |
|--------------------------|--|----------|
| 150 or less              | 36                                       | (24,7) * |
| 151-250                  | 34                                       | (31,9)   |
| 251-350                  | 11                                       | (24,6)   |
| 351-450                  | 8  | (9,3)    |
| 451-650                  | 6  | (8,4)    |
| 651 or more              | 5  | (1,1)    |

Source: du Plessis, C.M., Affordability - an essential element in a future housing process in South Africa  
Kruger, J., Supplement to MIE March/April, 1983, p.11

\* Figure in brackets relates to the population of Soweto only.

Source: Viljoen, A.F.V., Chairman's report of Committee to investigate private sector involvement in resolving the housing backlog in Soweto, 1982, p.15

The accepted minimum monthly income level necessary to afford a conventional house conforming to minimum standards is R450<sup>45</sup> (see 2.2.2) - thus 89 per cent of blacks cannot afford the procurement of their own houses, unless they are financially subsidised or have access to other financial resources.

According to figures released by the Central Statistical Services the average monthly income (gross salaries and wages) of blacks was R271 in June 1982, as compared to R137 in 1978,<sup>46</sup> an increase of 97,8 per cent over the four-year period. Over the same period, the CPI increased by 70,2 per cent (see Table 2.1.3). Thus the real increase in average gross monthly black incomes was only 27,6 per cent or an average annual increase of 6,9 per cent. The South African Institute of Race Relations claims that the average monthly household income for blacks was R112 in 1978 and R204 in 1982<sup>47</sup> (these figures are assumed to show net incomes), an increase of 82,1 per cent. A 70,2 per cent increase in the CPI reduces the average annual real increase in average monthly black real incomes to 3,0 per cent.

According to Professor Jill Nattrass, head of Natal University's Development Studies Unit, the average annual real increase in incomes from 1971 to 1981 was 5,5 per cent for blacks and 1,5 per cent for whites.<sup>48</sup> Mr. J.A. Grobbelaar estimates the average annual real increase in personal incomes for the period 1960-1980 to have been 4,1 per cent for blacks and 2,63 per cent for whites.<sup>49</sup> It thus seems evident that, in the sixties, white incomes rose relatively sharply by an average of approximately 3,5 per cent annually, whereas black incomes only increased annually by an average of 2,7 per cent in the sixties but rose sharply during the seventies. This trend, if continued, will result in a substantially more equitable racial income distribution by the turn of the century.

In relative terms the present average per capita personal income of whites is about ten times that of blacks. According to Mr. Grobbelaar the total personal income of all blacks, representing approximately 20,6 million persons in 1980, was R10 400 million in that year,<sup>50</sup> an annual average per capita income of R505. In 1980 all whites in South Africa earned a total personal income of R21 300 million. The annual average per capita income of the 4,5 million whites was therefore R4 733, resulting in a black/white ratio of 1:9,4. Assuming a 4,1 per cent average annual increase in black personal incomes, all blacks will earn a total of R38 000 million (at 1980 values) by the year 2000. The annual average per capita income of the expected 34,8 million blacks will therefore be R1 092. At an average annual increase of 2,63 per cent, white incomes will amount to R43 400 by the year 2000, an annual average per capita income of R7 891. Thus the black/white ratio will decrease from 1:9,4 in 1980 to 1:7,2 by the turn of the century.

The total economically active black population in South Africa (including all homelands) was approximately 6,5 million persons in 1980,<sup>51</sup> one-third of the total black population. The annual average per capita income of all economically active blacks was therefore R1 600, as compared to R11 210 for the 1,9 million economically active whites, representing a black/white ratio of 1:7. The National Manpower Commission report (1982) predicts that, by the year 2000, there will be 10,7 million economically active blacks and 2,4 million economically active whites.<sup>52</sup> Thus the annual average per capita income of all economically active blacks is expected to be R3 551, as compared to R18 083 for whites (at 1980 values), representing a black/white ratio of 1:5.

The black/white ratio in terms of per capita private consumption expendi-



ture is expected to decrease from 1:7,8 in 1980 to 1:6,6 by the turn of the century.<sup>53</sup> Taking only the economically active population into account, the ratio is expected to decrease from 1:5,8 to 1:4,4. It is predicted that, since blacks pay relatively less than whites in direct taxes and since black residual incomes are expected to be too low for substantial savings, the real spending power of South Africa's blacks will increase by 270 per cent from 1980 to 2000, as compared to an 118 per cent increase in white consumption expenditure.<sup>54</sup>

Although exact statistics and ratios are difficult to support for reasons previously stated, the brief foregoing analysis clearly shows the existence of an inequitable distribution of per capita wealth between blacks and whites. Even though the gap is narrowing, it is clearly evident that by the turn of the century the vast majority of the population will still be substantially poorer than a small minority.

In January 1983, the Director-General of Finance, Dr. Joop de Loor, warned the President's Council Economic Affairs Committee that South Africa's biggest economic problem was to raise the incomes and product of the black population.<sup>55</sup>

At present minimum wages in urban areas are being kept artificially low to stem the rate of influx of work-seekers from decentralised locations where minimum wage determinations do not exist, as an incentive to industrialists to establish factories in these regions. Thus the present homeland development policy exacerbates the chronic poverty problem in South Africa. It must be stressed that income earning capacity depends on the level of skill. Thus a dramatic increase in black incomes cannot be expected until training facilities are adequate to allow for higher incomes without a concomitant decrease in productivity which is already abysmally low.



#### 2.1.4.2.2 Housing Costs

"The fact is that the conventional brick, mortar and tile house is fast becoming a luxury and new cheaper building methods must be found and accepted." (56)

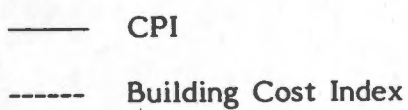
From June 1975 to May 1984 the CPI increased from 99,7 per cent to 288,3 (average CPI 1975 : 100), whereas the Bureau for Economic Research (BER) building cost index with a base year of 1975 rose to 294,8 in May 1984 (see Table 2.1.3). Thus over the last decade building costs have not increased substantially more than the average of all consumer goods and services.

Table 2.1.3 and the related graphs 2.1.2 and 2.1.3 show that, while the annual rise in building costs varied substantially, with the lowest increase of 2,4 per cent in 1977 and the highest increase of 31,2 per cent in 1981, the annual increase in the CPI showed a much steadier trend.

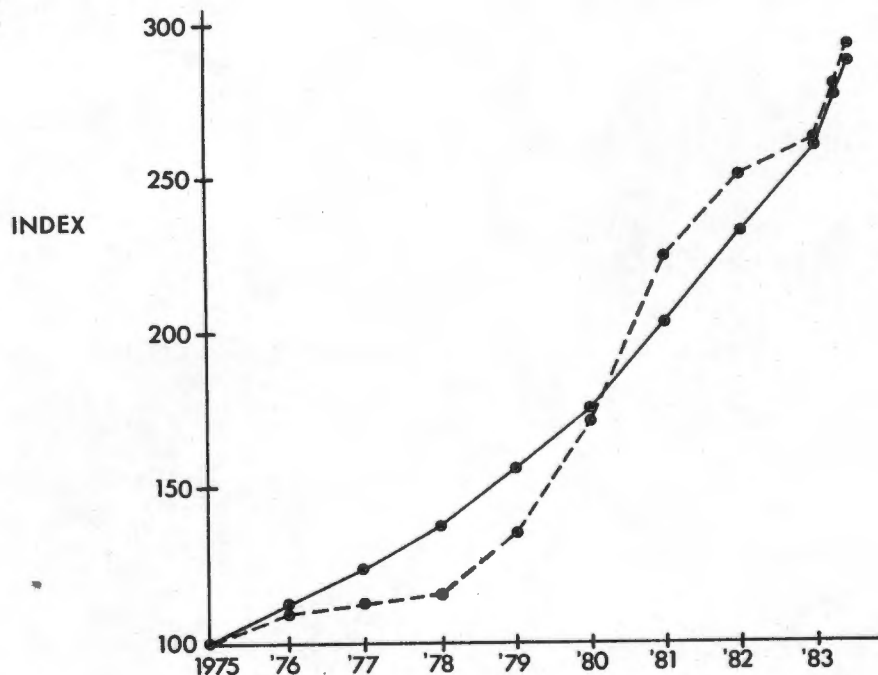
Table 2.1.3 CPI and BER Building Cost Index: 1975-1984

| Year       | CPI   | Annualised<br>% increase | BER Building<br>Cost Index | Annualised<br>% increase |
|------------|-------|--------------------------|----------------------------|--------------------------|
| 1975       | 100,0 |                          | 100,0                      |                          |
| 1976       | 111,1 | 11,1                     | 108,6                      | 8,6                      |
| 1977       | 123,7 | 11,3                     | 111,2                      | 2,4                      |
| 1978       | 137,2 | 10,9                     | 115,2                      | 3,6                      |
| 1979       | 155,3 | 13,2                     | 135,4                      | 17,5                     |
| 1980       | 176,7 | 13,8                     | 171,8                      | 26,9                     |
| 1981       | 203,5 | 15,2                     | 225,4                      | 31,2                     |
| 1982       | 233,5 | 14,7                     | 252,5                      | 12,0                     |
| 1983       | 262,2 | 12,3                     | 263,1                      | 4,2                      |
| 1984:1st Q | 278,4 | 10,2                     | 280,6                      | 10,5                     |
| 1984:2nd Q | 288,3 | 11,2                     | 294,8                      | 14,4                     |

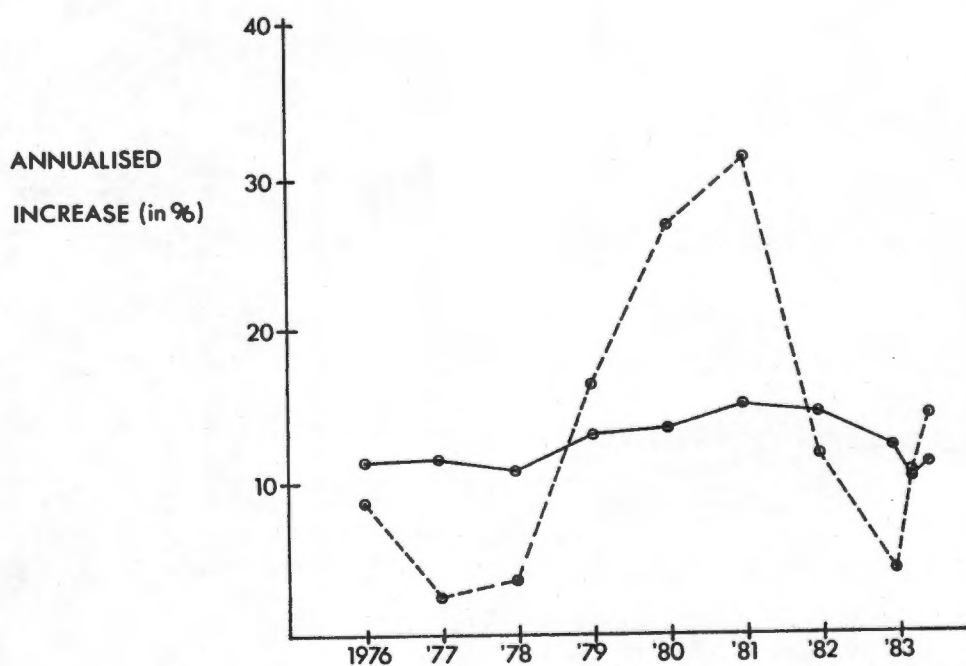
Source: CPI: Central Statistical Services, Pretoria.  
BCI: Bureau for Economic Research, University of Stellenbosch.



Graph 2.1.2



Graph 2.1.3



The cost of housing is however not only determined by building costs. Since the acquisition of a house is probably the largest single investment of most Western families, capital must usually be borrowed in order to be able to afford the house. Thus financing costs, in the form of monthly interest and redemption payments, add substantially to the cost of housing and determine whether or not a family can afford the procurement of its own house.

Both building costs and financing costs are greatly influenced by various factors, such as inflation, interest rates, the business cycle, by continued government attempts to use housing as a stabiliser for the overall economy (by so-called contra-cyclical expenditure) and by building design and standards.

The debate on minimum housing standards is well known to all those involved in low-income housing and underlies the objective of this study. As the private sector gets more involved in the low-income housing process (see 2.2), conventional building materials and methods of construction and minimum housing standards are being questioned. Traditional construction has been encouraged on a small scale outside the bounds of white metropolitan areas, reflecting tremendous savings in building costs. However due to the absolute extent of present and future housing needs, both conventional and traditional materials and construction techniques seem to be inadequate - what is required is a building system which combines low technology and high technology in a successful marriage. Some form of industrialised housing system, such as a mass-produced factory-manufactured 'kit' can provide according to the required scale of demand: in addition, high technology in manufacture and low technology in erection results in an ideal distribution of required skills (see 2.3).

In a report on demographic trends in South Africa the Science Committee of the President's Council suggests a 43-point plan for the implementation of an effective population control strategy. One of its recommendations is that 'housing standards should be reconsidered to provide more housing, not necessarily of a better quality, as a matter of urgency'.<sup>57</sup>

"The technical standards applied to Black housing should, as a matter of urgency, be revised so as to be less rigid and specific and so as to stimulate the use of innovative building methods, designs and materials." (58)

## 2.2. Low-income Housing Policy Developments: 1980-1984

### 2.2.1 Introduction: Financing of Low-income Housing

Due to the extent of the looming housing crisis, the government has recently revised its housing policy dramatically. State-subsidised mass housing programmes, which have dominated the low-income housing scene over the last three decades, came under close scrutiny around the turn of the eighties, as it became clearly evident that under present economic and political circumstances, the housing delivery system was inefficient and inadequate and that an attempt to tackle the housing crisis by means of conventional 'warfare' was doomed to frustration. Policy revisions are based largely on recommendations by the following committees or commissions of inquiry:

- Fouché Commission of Inquiry in 'Housing Matters' : RP 74/1977
- Viljoen Committee Report on 'Private sector involvement in resolving the housing backlog in Soweto' : RP 14/1982
- Steyn Committee on 'Financing of housing for members of the black communities' : RP 58/1983

- Louw Committee on 'Alternative methods of provision and of procurement of low-income housing' : unpublished/1983
- Venter Commission of Inquiry into 'Township establishment and related matters' : RP 20/1984, RP 21/1984, RP 52/1984

Finance for State-subsidised housing is provided by the Treasury via the National Housing Commission to various administration boards (or development boards) and local authorities. All expenditure incurred by this body in the provision of housing is met from the National Housing Fund, which functions in terms of the National Housing Act 1966 and is administered by the Department of Community Development and State Auxiliary Services. Under the new Constitution, the Department of Community Development has been replaced by separate 'Housing' sections for whites, coloureds and Asians under the broad wings of the Public Works Department. On 1 September 1981 the Cabinet transferred full responsibility for the black housing programme in South Africa, financed by the National Housing Fund, to the Department of Co-operation and Development.

On 1 August 1983 the Black Local Authorities Act (No. 102 of 1982) came into effect, providing for the phasing out of community councils and replacement with town or village councils. This new system of local government for blacks is similar to that of municipalities for other race groups, with certain powers being conferred directly on the new black local authorities, thus giving them greater status and autonomy than community councils had. Amongst the powers with which new local authorities have been vested are the responsibility for services (waste disposal, sewerage and electrification) and housing administration, both previously functions of the administration boards.

### 2.2.2 State-subsidised Low-income Housing: 1980

A subsidisation system lies at the heart of the low-income housing policy in South Africa. The general form of the system is now well established, being a differential scale of subsidisation based on income characteristics. Broadly speaking, two categories of subsidisation exist:

- 'economic' housing
- 'assisted' housing

The boundary between these two categories of subsidisation is presently defined by an income level of R450 per month. The term 'sub-economic housing' was made redundant when the sub-economic interest rate of 1 per cent was abolished in October 1980.

In 1980 two major policy adjustments were instituted:

- (a) 1 July 1980 - the first ever state-subsidised low-income home purchase dispensation was introduced (see Department of Community Development Circular Minute No. 9 of 1980).
- (b) 1 October 1980 - major revision of interest rates for rental calculations (see Department of Community Development Circular Minute No. 10 of 1980).

(See Table 2.2.1)

Table 2.2.1 State-subsidised Low-income Housing Catagorisation: 1980

| Type of Subsidy   | Monthly income<br>of household<br>head (in R)               | Interest<br>rate (%)                                       |
|---|---|--|
| (a) Interest rates on loan repayments for <u>Home-purchase</u> :<br>since 1 July 1980 | 0 - 350<br>351 - 450<br>451 - 650*                          | 5<br>7<br>9  |
| (b) Interest rates used in <u>Rental</u> calculations:<br>since 1 October 1980        | 0 - 150<br>151 - 250<br>251 - 350<br>351 - 450<br>451 - 650 | **<br>3½ *** (i)<br>5 *** (ii)<br>7 *** (ii)<br>9 *** (ii) |

\* Income limit of R540 was increased to R650 on 18 September 1980 and up to R800 a year later.

\*\* Basic monthly rental is 5 per cent of income (R2,50-R7,50) to which a service charge is added.

\*\*\* Redemption period:  
Calculation of rentals based on a percentage of the depreciation replacement cost of a house:

(i) over 40 years

(ii) over 30 years

#### NOTES:

- 'Fixed Scale' annuity system: The sliding scale system for rental calculations has been replaced by a fixed scale system which is to be revised annually. This fixed annuity system however may result in a considerable increase in rental after a negligible increase in income, because of a higher applicable rate of interest - thus a 'cushion effect' is incorporated, which operates as follows:

If monthly income increases from less than R150 to more than R150 but less than R250, the resultant increase in rental would be substantial. Thus the increase is limited to R2 per month for every R10, or portion thereof, by which the increased income exceeds R150 per month. The monthly rental is adjusted annually by at least R2 per month until such time as the full rental, based on a  $3\frac{1}{2}$  per cent interest rate, is levied.

In any other case where an increase of more than R10 per month is caused by the adjustment, the increases are limited to R10 per month. The rentals of such tenants are adjusted annually by at least R10 per month until such time as the full rental applicable to the relevant income group is levied.

- Valuation of dwelling units: Dwellings less than two years old are classified as new dwellings and rentals and loan repayments are calculated on the cost thereof including cost of land and services, as prescribed in the Housing Code. Rental and loan repayment calculations for dwellings two years and older are based on the depreciated replacement value (DRV) thereof. The DRV relates only to the cost of the dwelling - in order to determine the total valuation of the property as a whole, the value of the land (taken at municipal valuation) as well as the cost of external services must be added to the DRV. If the DRV of a dwelling unit is less than the original cost, then rentals and selling prices are calculated on the original cost.

In the case of the black population group the cost of the land and services is recovered in a different manner and is therefore not taken into consideration when calculating the selling prices of the dwellings - the valuation formula is therefore only applicable to the



building. Dwellings sold under the special selling programme of 500 000 units are valued in accordance with the same formula, but various rebates may be granted (see 2.4.3.4).

- Subsidisation of Services: Housing funds for the provision of external services in township developments are made available by the National Housing Commission at an interest rate of 9 per cent. In February 1982 a differentiated subsidisation system for services was introduced, only to be abolished three months later. The costs of services are then included in the cost of the housing projects and repayments to the Department of Community Development are effected in accordance with the provisions of the rental or home-purchase formula.
- Household-head Income: In calculating loan repayments and rentals only the income of the household-head or breadwinner of a family is taken into consideration. It has been suggested that cognisance should be taken of total family income which includes a wife's income and other regular financial resources - banks and building societies are already offering loans on this basis.
- 25 per cent Rule: All monthly rentals and instalments as regards loan repayments for home-purchase are limited to an amount not exceeding 25 per cent of the tenant's or borrower's monthly income. This empirical ratio is however only reasonably justified for salaries over R750 per month, as lower income groups have a relatively smaller residual income. The financial burden of bridging the gap between actual income and that required according to the 25 per cent rule is proving to be enormous.

Table 2.2.2 defines a more realistic relationship between income and maximum affordable percentage for housing.

Table 2.2.2

| Income (in R)                        | 150 | 200 | 300 | 400 | 500 | 600 | 750+ |
|--------------------------------------|-----|-----|-----|-----|-----|-----|------|
| Maximum affordable on housing (in %) | 9   | 10  | 12½ | 15  | 18  | 22½ | 25   |

(59)

- Cost - and Loan - Limits: Due to rapidly rising housing costs, the maximum permissible cost limit of houses erected with State funds, and related maximum loan limits, are updated regularly. During 1983 the respective limits were R33 000 and R29 700 with an income limit of R800 per month.<sup>60</sup> In respect of loans made available by the National Housing Commission and building societies jointly the respective limits are R35 000 and R31 500 with an income limit of R900 per month.

### 2.2.3 Low Income Housing Policy Adjustments: 1982

In 1982 two major policy adjustments affecting the provision of black housing were made:

- (a) A new decentralisation policy was announced.
- (b) 'Self-help' building projects were officially instituted as an alternative housing delivery system.

### 2.2.3.1 Decentralisation Policy Adjustment

The government has finally admitted that attempts to promote the decentralisation of industrial growth points have largely failed and consequently a greatly revised policy, based on a stronger economic - and less ideological - approach, has been announced. Economically more suitable decentralised growth centres have been defined with the aim of achieving 'a more balanced geographical distribution of economic activity' in South Africa. The formation of the Development Bank of Southern Africa by the governments of South Africa, Bophuthatswana, Transkei, Ciskei and Venda, as well as the establishment of a Decentralisation Board clearly represent further very important steps in the government's decentralisation programme.

Although it is far too early yet to come to conclusions, the policy based as it is on new and better placed growth points may well prove to be successful. In the light of the vast black population growth and rapid urbanisation, the effective decentralisation of urban communities must be seen as the most important pre-requisite to a successful attempt at solving the housing problem in white urban centres. The present policy of legislative influx control over blacks in white urban areas cannot prevent rapidly increasing urbanisation rates in these areas, unless sufficient job opportunities are created in decentralised locations, and sufficient houses, utilities and amenities are provided to promote the development of self-sufficient, economically and socially stable communities (see 2.1.3).

### 2.2.3.2 'Self-help' building

In July 1982 the Minister of Community Development announced the incorporation of 'self-help' approaches as a recognised and state-encouraged

housing alternative. The debate on the merits and demerits of 'self-help' housing has been under the spotlight for almost ten years and is well known to all who are involved in low-income housing.

"Controlled and properly supervised self-help and owner built participation should be encouraged and accepted as a normal part of the housing process." (61)

The provision of State-subsidised completed dwelling units on a massive homogeneous scale is to a large extent an inefficient delivery system, because the inhabitants are given no opportunity of becoming actively involved in the housing process. The conventional housing process presently takes the form of capital-intensive mass building programmes, financed by the State and run by white profit-making firms. The net effect of this is an increased outflow of capital from the poorest areas, greater inequality in income distribution and a worsening housing problem.

"For Blacks, the present delivery system and conditions of occupancy have resulted in a low degree of control over their own affairs and greater dependence upon the housing authorities . . . While it is accepted that the lack of purchasing power amongst Blacks has led to this dependence, public housing has resulted in Blacks being ill-equipped to develop economically and socially alongside Whites, who have always exercised a high degree of control over their own affairs." (62)

A housing policy could be judged effective if it gives the inhabitants a feeling that they have the capacity to influence the aspects of their environment which affects them directly. The policy should be aimed at redistributing income and using resources with maximum benefit. An effective way of doing this and one which is consistent with developmental principles, is to utilise the time, energy and skills of the poorest people, whose alternative marginal product is often very low, to tackle their own

building programmes. The 'sweat equity' induced by 'self-help' building could be a substantial factor in reducing housing costs. In addition, the opportunity of changing from being a passive recipient of public housing to becoming an active decision-maker with regard to his housing needs will establish a much closer and more natural relationship between the occupant of a dwelling and the house itself. In this way individuals become more adapted to the urban environment and a community spirit develops as individual choices are made according to personal assessments of needs, means and aspirations.

The conventional housing delivery system results in most public effort and investment being put into the house itself, which is but a small part of the housing problem and can usually be better and more economically handled by the individual than by a public agency or by profit-making private enterprise. The real effort is required in those areas in which the individual cannot help himself - in the creation of job opportunities and in the provision of utilities and amenities. Policy objectives should therefore centre around how best to allocate limited resources and how to maximise opportunities for individuals and communities to participate effectively in the whole process. There are a number of pre-conditions for the implementation of a successful 'self-help' housing programme:

- Low interest loans on services.
- Secure tenure.
- Access to loans.
- 'Reasonable' standards.
- Technical assistance - bulk buying, advice, supervision, etc.

"Private home-ownership continues to be the ideal pursued by the vast majority of South Africans although factors such as extremely high plot prices, rising housing costs, expensive essential services, shortages of loan funds and high rates of interest on mortgage loans have had their effect on the extent to which this ideal can be attained, it has never lost its appeal."(63)

Complete security of tenure is probably the most fundamental prerequisite to a successful housing policy. One of the most detrimental effects of restricting home-ownership, is that a high degree of insecurity aggravates the overriding problems of poverty and racial inequality of opportunities. Firstly, a high rental to ownership ratio in the housing stock and high maintenance and obsolescence costs (which arise from the tenant not investing time, energy or capital in the upkeep of the dwelling), leads to increased rentals. Secondly, people with no security of tenure have no investment outlet in their dwelling - the monthly cost of rented accommodation represents one of the largest items of expenditure on low-income families' budgets; what could be an investment becomes simply a running expense. The ownership of property and houses is the basic form of wealth of most families in the Western world, being probably the greatest personal investment made in a lifetime. In addition to the economic benefits of a relatively secure capital investment over time, the potential for capital appreciation encourages property-owners to protect their investment by maintaining and improving their properties. Even a family with very little capital can, over time, acquire an asset of considerable exchange-value, while at the same time being able to take advantage of its use-value.

The extent of research and development on 'self-help' building is clearly illustrated by the volume of reports, books and manuals published. A handbook on self-help and self-build developments, compiled by the Institute

for housing in collaboration with the Urban Foundation, was recently published. The book entitled 'Guidelines for Self-help Housing' provides a sound basis for the future planning and implementation of 'self-help' housing programmes in South Africa.

Although various 'self-help' housing projects have been instituted over the past five years by the Urban Foundation and by the Department of Co-operation and Development and administration boards, amongst others, the scale of activities has been minimal. However due to the official stamp of approval granted by the Department of Community Development recently, the scale of 'self-help' building activities should increase dramatically in the near future. The proposed construction of 4 800 core houses at Khayelitsha, near Cape Town by the Western Cape Development Board, funded by the National Housing Commission to the tune of R60 million, is a clear indication that 'self-help' building is now being officially encouraged as an alternative low-income housing system for blacks in South Africa.

#### 2.2.4 Low-Income Housing Policy Adjustments: 1983

In 1983 another two major policy revisions as regards the provision of low-income housing were announced:

- (a) Provision of more serviced sites in lieu of completed dwelling units (see Department of Community Development Circular Minute No. 1 of 1983).
- (b) Sales campaign of 500 000 dwelling units to members of the black community, amongst others (see Department of Community Development Circular Minute No. 17 of 1983).



#### 2.2.4.1 Priority Reallocation: Provision of More Serviced Sites

In January 1983 the government reiterated that sufficient public funds to provide for the ever increasing cost of - and demand for - low-income housing could no longer be afforded and that private sector contributions were desperately required to tackle the housing problem, not with minor 'skirmishes', but full-scale 'warfare'. With this new approach in mind the following priorities for the utilisation of State funds were determined.

- In the first place, funds are to be utilised to make serviced building plots available to enable individuals, earning more than R150 per month, to purchase stands upon which they can erect their own houses with their own funds or with finance obtained from other sources such as banks, building societies and employers. The standards to be applied will take due cognisance of the income groups for which the building plots are required.
- The second priority is to allocate funds to house needy persons such as the aged and pensioners who cannot provide for themselves.
- The third priority is to assist persons who are prepared to help themselves, but who cannot obtain financial assistance from private sources. Self-builders are not granted cash, but 90 per cent individual loans are made available by the National Housing Fund to local authorities who utilise the funds to assist self-builders in the purchase of building materials and in providing the necessary technical assistance. The maximum amount of loans was increased from R500 to an amount left to the discretion of local authorities (often up to R4 000 or more).
- Lastly, funds will be utilised to provide completed housing for the lowest income groups - families with a monthly income under R150.



#### 2.2.4.2 Sales Campaign: 500 000 Dwelling Units to Members of the Black Community, amongst others

In March 1983, acting on recommendations of the Steyn Committee, the government decided to institute a sales campaign involving approximately 500 000 dwelling units presently used for rented accommodation. 300 000 of these units are presently occupied by black tenants earning more than R150 per month, who are encouraged to buy their dwelling under the 99-year leasehold system.<sup>64</sup> A selling programme is being conducted over a period of two years, ending 30 June 1985, to promote the sales campaign. Present tenants have the only option to purchase the dwellings, unless a tenant is prepared to agree in writing to move voluntarily to another unit in order that his dwelling unit may be sold to someone else.

#### Selling Prices

Selling prices of all units erected less than two years ago are determined on the actual cost of erection, but must be adjusted in accordance with the formula prescribed below when the age of two years is reached.

Selling prices of all units which are two years and older after 1 July 1983 are determined on an annual basis. The valuation or selling price is based on the average of:

- the original cost of erection of the dwelling unit, and
- the present replacement value of the property calculated at the factors listed in Table 2.2.3. - these factors are to be revised in June 1985.

Table 2.2.3 Replacement Cost Factor: 1982

|        |      |     |     |     |     |     |     |     |     |     |     |     |
|--------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Year   | 1982 | '81 | '80 | '79 | '78 | '77 | '76 | '75 | '74 | '73 | '72 | '71 |
| Factor | 1,0  | 1,0 | 1,5 | 1,9 | 2,0 | 2,0 | 2,0 | 2,5 | 2,8 | 3,3 | 3,7 | 3,8 |

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|        |      |     |     |     |     |     |     |     |     |     |     |     |
|--------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Year   | 1970 | '69 | '68 | '67 | '66 | '65 | '64 | '63 | '62 | '61 | '60 | '59 |
| Factor | 4,0  | 4,7 | 5,0 | 5,0 | 5,5 | 5,8 | 6,0 | 7,0 | 7,0 | 7,4 | 7,4 | 7,3 |

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|        |      |     |     |     |     |     |     |     |     |             |  |  |
|--------|------|-----|-----|-----|-----|-----|-----|-----|-----|-------------|--|--|
| Year   | 1958 | '57 | '56 | '55 | '54 | '53 | '52 | '51 | '50 | and earlier |  |  |
| Factor | 7,0  | 7,0 | 7,5 | 7,5 | 7,5 | 7,7 | 7,0 | 6,7 | 7,7 |             |  |  |

Example:

Dwelling erected in 1970 at a cost of R 5 000

Replacement cost: R5 000 x 4,0 R20 000

Total R25 000

Average R12 500

After the price has been determined, as prescribed, the following rebates may be granted:

- 25 per cent reduction for cash sales, except in respect of dwellings with a valuation below R2 500 which must only be sold for cash and in which case a 30 per cent reduction may be granted.
- 5 per cent reduction to a purchaser who has rented the dwelling for longer than 5 years.
- 5 per cent reduction to a purchaser who buys within the special sales programme period.

NOTES:

- If the price of the dwelling is below cost after rebates have been calculated, the dwelling unit must be sold at cost price.

- Rebates are only applicable to those transactions concluded during the duration of the selling programme.
- In the case of the black population group, the cost of the land and services is recovered in a different manner and is therefore not taken into consideration when calculating the selling prices of the dwellings. The valuation formula is therefore only applicable to the building.
- The financing of sales by purchasers with an income of more than R450 per month will not be undertaken by the National Housing Commission, unless evidence is furnished that no finance can be obtained elsewhere.
- Buyers must be persuaded to pay cash for these properties in order to qualify for the cash rebate of 25 per cent. The cash may be obtained from banks, building societies, employers or from personal savings, thus encouraging private sector participation.
- A limited number of dwelling units (approximately 20 per cent of existing stock) will still be kept available for letting purposes. The major drawback as regards the sales campaign, is that the sale of existing rented houses does not provide one additional house to the present stock. However it is assumed that the proceeds from the sales campaign will be channelled back into the financing of new dwellings within the parameters of recently revised priorities for the allocation of funds - serviced sites and self-help building in lieu of completed dwellings.
- As from July 1983 (start of special sales programme) the interest rates on loan repayments for home purchase and for rental calculations have been slightly adjusted as follows:

- Loan repayments for families with a monthly income of less than R350 were previously calculated at an interest rate of 5 per cent - for families with an income of less than R300 per month this rate of interest has been reduced to  $3\frac{1}{2}$  per cent.
- The income limit of R650 has been increased to R800 per month for both loan repayment - and rental - calculations, which are based on the latest 'economic' interest rate of 11,25 per cent.
- Rental calculations are still largely based on revisions made in 1980. Rentals will not increase in accordance with the revaluation of dwellings for selling purposes. A revision of the rental formula and related subsidised rates of interest, proposed to come into effect on 1 July 1984, were not implemented as intended - however when this revision does come into effect (probably in June 1985), drastic rental increases are foreseen.

### 2.2.5 Conclusion

In theory the developments in the government's low-income housing policy since 1980 have been extensive, if not dramatic. Official promotion of 'self-help' building, encouraging private sector involvement and promoting widespread black home-ownership with 99-year leasehold rights, are all revisions of relatively recent heritage.

However in practice the policy has not been adjusted sufficiently to allow these developments to bear fruit. The public sector has kept firm reins on the delivery system, thus maintaining an artificially inflated housing market which undermines the operation of an open market. The private sector cannot afford to support direct subsidisation - thus to keep costs

within affordable limits, lower minimum standards of housing must be accepted. Individuals and private industry are willing to harness their technical, financial and managerial resources to supplement public sector activities. However in taking some responsibility for the provision of low-income housing, the private sector must be given an equal amount of authority in the process. Instead of dictating the rules of the delivery system, the authorities should encourage privately instilled control by allowing greater autonomy in decision-making. Private industry, especially the building industry, knows the importance of control over materials, workmanship and detail. Thus before any substantial private sector participation occurs, a more realistic housing market must be established, governed by economic realities, not by political ideologies.

The recent government decision to place the responsibility of financing and providing houses for black families earning more than R150 per month into private hands (see 2.2.4.1), means that the rotten apple has simply changed hands. Without a concomitant increase in authority, allowing the private sector to institute basic policy changes, this transfer of responsibility will result in the private sector failing just as dismally as the public sector did - not the best medicine for an ailing society. Being forced to operate under present minimum housing standards and outdated building regulations, the private sector will not come forth to embark on 'Project Failure'. Basic policy changes must be instituted, such as allowing the individual and private industry to use their initiative and expertise to determine what they can effectively afford and what their personal needs and aspiration are.

Mr. Pen Kotze, Minister of Community Development, recently admitted that there was an urgent need 'to promote rapid, even dynamic, housing

development in which all the resources of the private and public sectors are used'.<sup>65</sup>

At present the public sector owns almost all the land zoned for black residential use, but does not have sufficient financial - or other - resources to build enough houses on this land. While the majority of public land lies fallow the private sector desperately needs more land for development. Furthermore, some of these idle sites have already been developed with a basic infrastructure of utility services but because the land belongs to the Department of Co-operation and Development, the private sector cannot continue with the development of housing and social services. Since the public sector has total control over the allocation of land for development the private sector hesitates to criticise the delivery system, for fear of discrimination when land is made available and contracts are handed out.

In essence there is at present very little major urban black housing development under way in South Africa except at Khayelitsha ('New Home') in the Western Cape, where the construction of 40 000 core-houses at an approximate total cost of R500 million over the next twelve years is planned, to eventually accommodate a population of 250 000.

### 2.3 Industrialised Housing: An Alternative

"In view of the fact that 'house' was the largest material acquisition of man's lifetime and that it was completely outside the industrial scope, when everything else that man was doing was within the advantage of industrial scope it seemed to me the fundamental incompatibility of this basic economics would cause war and trouble for a long time to come unless something revolutionary was done about it." (66)

Industrialised building or 'Systems' building involves the manufacture of components of a building in a factory and the subsequent assembly on a

building site. Industrialised building systems can be classified in two basic types:

- Heavyweight - panels made of concrete or masonry; developed mainly in France, Britain and in other European countries.
- Lightweight - panels made of timber, fibre-reinforced cement or sheet metal; developed mainly in the United States of America.

In South Africa the emphasis thus far tends strongly towards the 'heavy-weight' industrialised housing systems of European heritage. However there is a pertinent difference in approach to the provision of accommodation - in Europe low-income accommodation largely takes the form of high-density, high-rise buildings, whereas in South Africa the low-rise housing approach predominates.

"The South African market has tremendous potential, but co-ordinated planning, development and management of manufactured home projects is vital to provide local home seekers with an attractive residence and worthwhile investment."  
(67)

In the context of this study, only a lightweight, low-rise industrialised housing system pertains, as it seems to be neglected as a housing alternative and one which has distinct advantages in providing for the housing needs in South Africa. There are a number of reasons to assume that this building system is a feasible alternative:

- There exists a serious skilled labour shortage to meet the country's enormous demand for housing by conventional means. The most significant effect of industrialised building is the reduction in the demand for on-site skilled labour and is thus ideally suited to 'self-help' building operations.



"A characteristic of lightweight building systems is that the actual site operations take up only a small proportion of total construction time as most components are factory made metal sheets, asbestos components, woodbased laminates, etc., which are light and easily assembled later on site. There will therefore be a drastic reduction for site skilled building labour." (68)

Job opportunities are inherently limited to the scale of economic activity, resulting in increased unemployment largely amongst unskilled - and usually unhoused - workers as the process of urbanisation takes its course. The adoption of industrialised 'self-help' housing systems in South Africa has the potential of killing two birds with one stone by providing firstly, more job opportunities for unskilled and semi-skilled labour, while easing the demand for scarce skilled labour and secondly, more new houses for those families presently classified as 'unhousables'.

- Time saving - although it is generally accepted that industrialised building methods tend to be faster than conventional methods, the degree of time saving is open to speculation and must be related directly to the type of industrialised building system employed. However it is broadly assumed that the average reduction in on-site time is approximately 50 per cent<sup>69</sup> - manufactured 'kit' systems could result in even greater savings (see 7.2 and 7.3).
- Cost saving - it is by no means conclusive that industrialised building is cheaper than conventional building. Although initial manufacturing and erection costs are generally lower, it is difficult at this stage to profess emphatically that long-term costs over the useful life of the building, including original cost, maintenance and obsolescence costs, are significantly reduced, if at all. However 'time is money' and in the light of an enormous demand for more houses

and a potentially more adequate scale of supply by means of industrialised building, the system could be rated as being at least as effective as conventional building in terms of investment on a cost/benefit basis (see 7.2 and 7.3).

The third Venter report (October 1984) states that 'a considerably cheaper form of accommodation for average families is made possible by using prefabricated living units' and summarises the benefits of manufactured housing as follows:

- The erection cost of conventional dwellings are escalating far more rapidly than the manufacturing costs of factory-built homes and have already reached so high a level that the average family has no hope of affording a conventional dwelling.
- Modern manufacturing techniques (such as automation) make it possible to exercise better control over the production costs of a factory-built home than over the construction costs of conventional homes - especially where large-scale production takes place.
- Factory homes are far more rapidly constructed on sites and this factor also contributes to cost saving.
- Since prefabricated living units can be purchased in modules it is easier for a prospective owner to adjust the size of his original home and future extensions to his financial means.<sup>70</sup>

There are a number of major problems in the establishment of any industry, and an industrialised building industry is no exception:

- The initial capital cost of establishing factories with modern machines and trained operators is enormous. Thus large-scale mass housing programmes are essential in order to spread the cost of

capital outlay and to take advantage of economies of scale. The major parameter as regards this requirement is the provision of serviced sites on a massive scale.

- The increased demand for managerial staff and technologists to plan, develop and co-ordinate a 'systems building' industry is probably the most limiting factor to the effective implementation of the concept in South Africa.
- In addition, trained supervisory staff must be provided on a large scale, as extreme care must be taken to avoid quality of materials and of workmanship being sacrificed for an overriding need for increased speed of provision - in the long term the most economical house is not necessarily the one requiring the least initial capital input. The quality of factory production and of on-site assembly must therefore be carefully controlled - this calls for adequate supervision.

"Industrialising man - like a salmon - 'swims upstream' to regenerate." (71)

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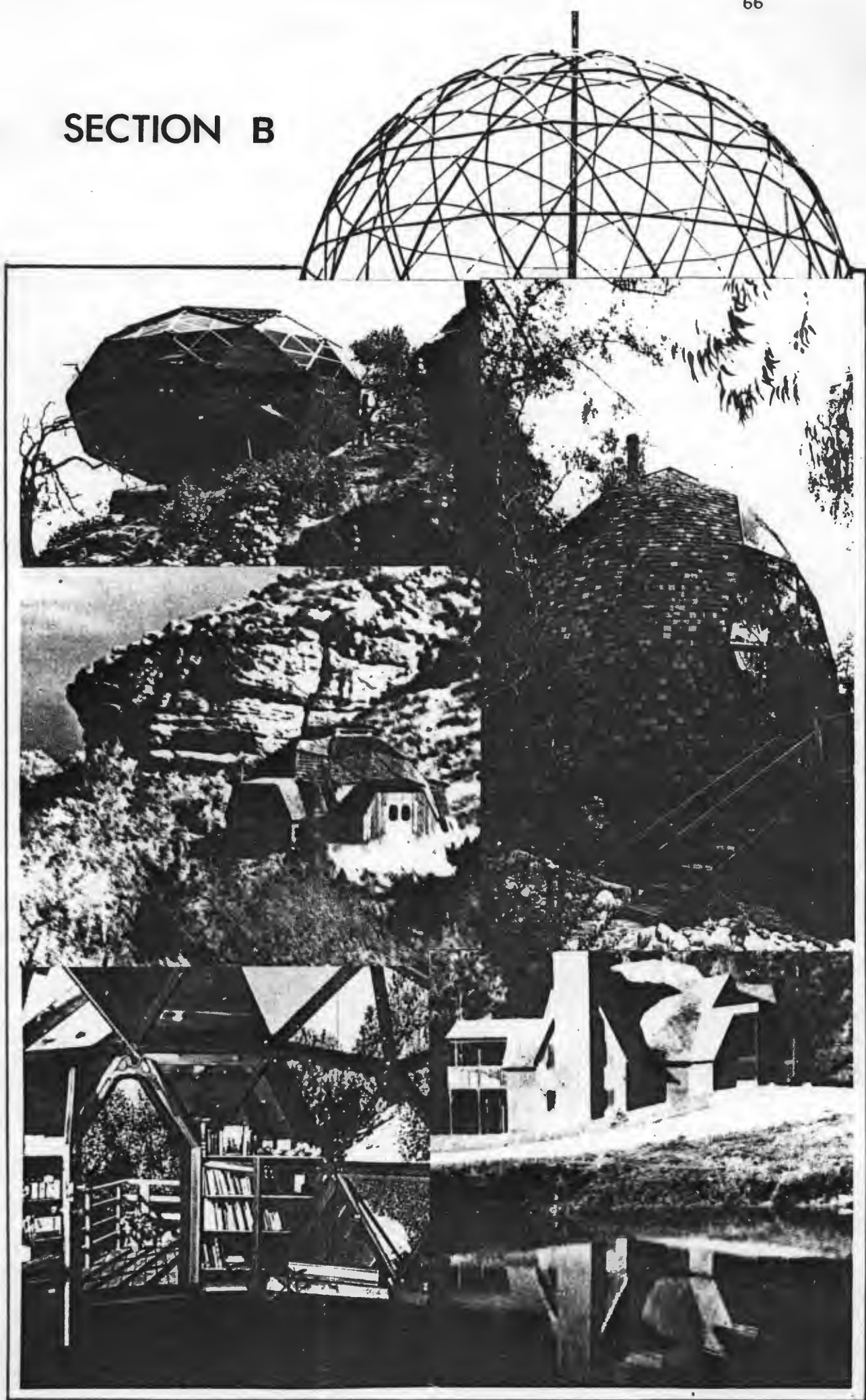
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## SECTION B



## CHAPTER THREE

### 3. THE GEODESIC DOME : HISTORICAL

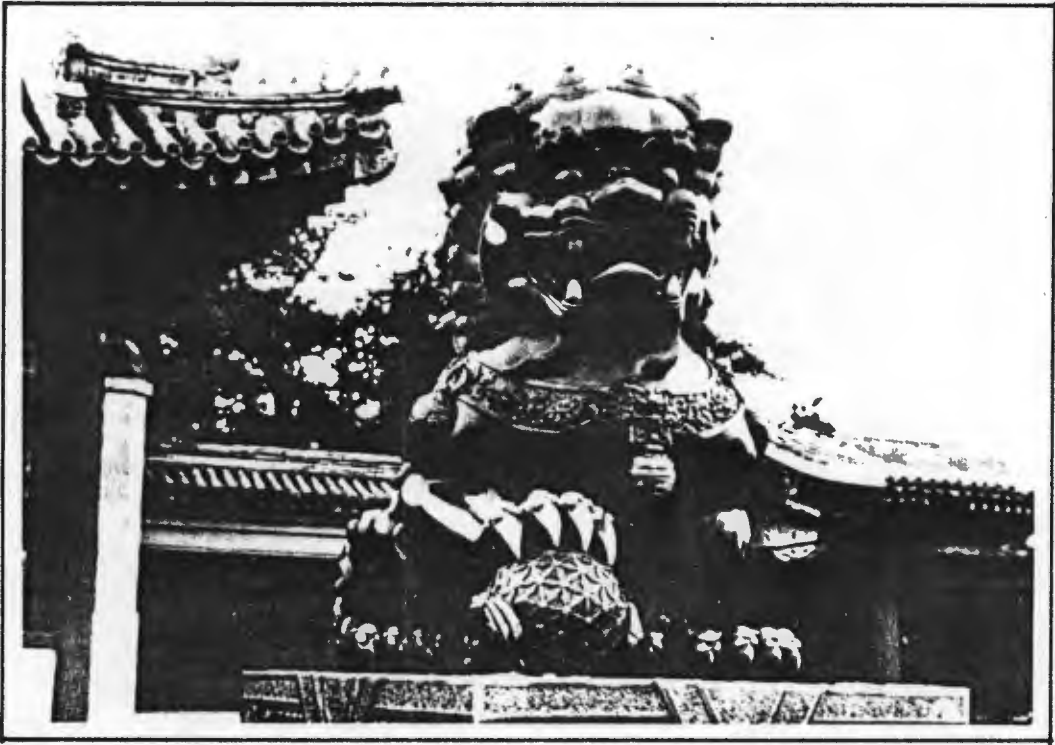
'Great circles' are the largest possible circles that can be drawn upon the surface of a sphere. Every great circle cuts the sphere exactly in half, so the term used by scientists and mathematicians to describe these curves is 'geodesic', which comes from the Greek for 'earth-dividing'.

The great circle principle has been used for many centuries to weave fish traps, hats, baskets and shelter; in nature the three-way geodesic grid manifests itself in all structuring, from the outer tissue of the human testes to the cornea of the eyeball, from the atom to the Universe.

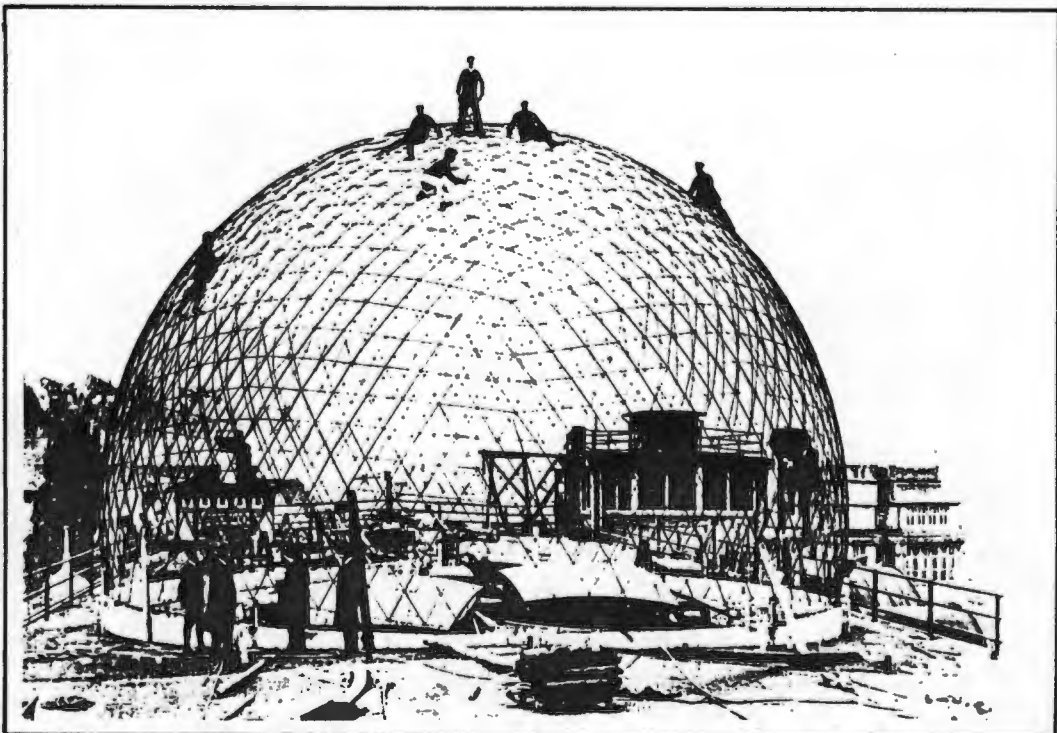
The first recorded man-made geodesic sphere can be seen at China's summer palace on the outskirts of Peking - in about 1885 the Empress Dowager commissioned to have a sculpture of a lion, holding a clearly recognisable geodesic sphere under his claw, erected here.

In 1922 a most remarkable geodesic dome was built on top of the roof of the Zeiss optical works factory in Jena (now East) Germany, to serve as a planetarium. The inventor and designer of this dome, Dr. Walter Bauersfeld, however did not commercialise the geodesic concept. The 'Wonder of Jena', as the planetarium became known, was a 50 ft. (15,25 m) - diameter, 16-frequency geodesic structure, derived from the icosahedron. In 1951 Richard Buckminster Fuller filed a United States patent on the

3.1 Lion sculpture outside China's Summer palace, illustrating first recorded geodesic dome, 1885



3.2 'Wonder of Jena' dome, East Germany, 1922



design of what he terms 'geodesic' domes - his icosa-based structure also had a 16-frequency edge-subdivision because 'at an edge-frequency of sixteen, the surface of the geodesic planar-faceted dome becomes indistinguishable from the surface of a sphere'.<sup>1</sup> In addition, the patent refers to a structure with a maximum diameter of 50 ft. although much larger structures have subsequently been built.

"Fuller's contribution, rather than origination of the great circle principle, or its earliest structural utilisation, is rather the application of the word 'geodesic' to this type of polyhedral building framework, and its popularisation and commercialisation in the United States." (2)

From 1927, at the age of 32 years, Fuller set about to direct his experience in ship-building, aeronautics and astronomy towards a 'comprehensive anticipatory design science' in building. He had experienced the messy world of ignorance and superficiality in houses when his daughter died of pneumonia in 1922. He blamed her death on his inability to maintain suitable health conditions in the kind of dwellings he could afford.

"The more I saw of the housing world the more it seemed to me that about this great ignorance much could be done if we could think of our whole economies in terms of a preventative pathology instead of a curative pathology." (3)

Consequently Fuller began to design houses which were stressed like an airplane with compression parts and tension parts separated out. By observing the energy patterns in nature, he discovered that tension and compression were complementary functions of structure (see Appendix B). He believed that man-made, land-based structures should be based on these integrities of nature.

Fuller applied this premise to his multi-deck apartment houses which had a central mast in compression from which hexagonal deck planes were sus-

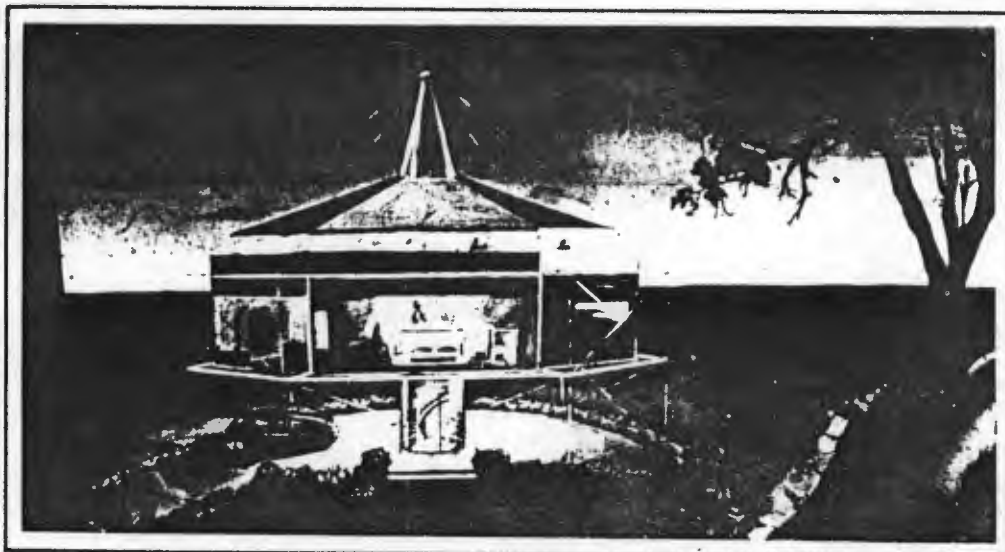
pended by tension cables. The decks were designed according to the wire-wheel principle, thus requiring at least twelve tensional spokes to stabilise the hub position in relation to the rim, both of which are in compression. The mast was supported by taut guy-wires which provided the balancing tension. The 4D Dymaxion house, the design of which Fuller completed in 1928, was structurally based on the same tensionally-cohered horizontal wire-wheel principle, but with only two suspended decks. The house was designed to contain a die-stamped Dymaxion bathroom complete with all fixtures and facilities. However at the time materials science was technologically not sufficiently advanced for the industrial production of the 4D house, because Fuller specified aluminium alloys and plastics as yet unrealised, but which seemed to him quite reasonable to expect in the near future. Fuller predicted that it would take 'at least 25 years before the gamut of industrial capabilities and evolutionary education of man - as well as political and economic emergency necessities - would permit the emergence of the necessary physical paraphernalia of this comprehensive anticipatory design science undertaking'.<sup>4</sup>

In 1940-41 Fuller designed the Dymaxion Deployment Unit and the Twin Dymaxion Deployment Unit for wartime use as radar stations, dormitories, hospitals, etc. Designed as a form of industrial mass-produced emergency shelter, an output of 1000 units per day was reached, until the United States government reallocated steel priorities to the pressing demands of the munitions and the aircraft industries - thus the production of the DDU was abandoned.

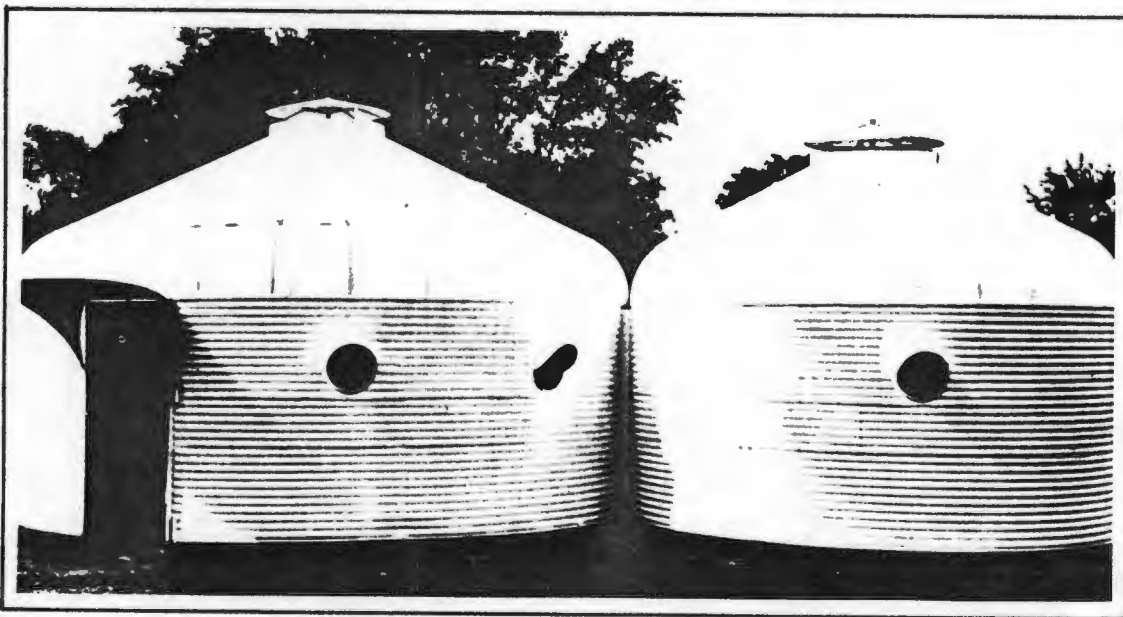
Fuller went on to design a scheme for the postwar conversion of the aircraft industry to housing purposes. As a result, in 1944, he was invited by the Beech Aircraft plant at Wichita, Kansas, to explore the possibilities of his scheme. The plant was being plagued by a serious labour shortage



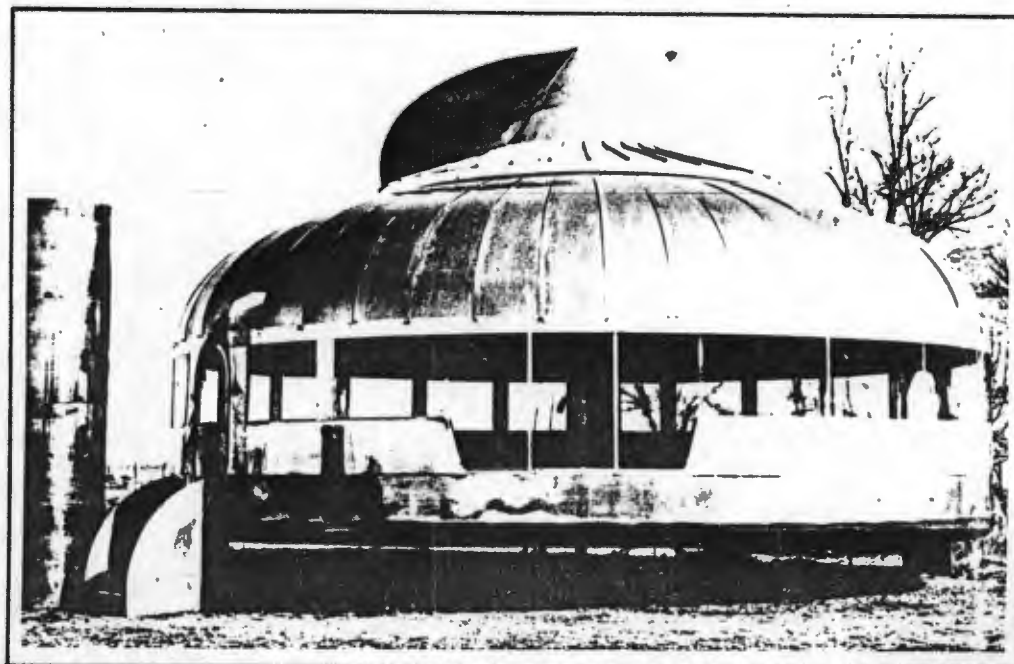
3.3 4D Dymaxion house, 1928



3.4 Twin Dymaxion Deployment Unit (DDU), 1940-41



3.5 Dymaxion Dwelling Machine (Wichita house), 1944



due to the lack of worker accommodation. The Witchita house or Dymaxion Dwelling Machine was a development of the 4D house. Fuller discovered that by increasing the diameter of the mast-and-wire complex of the 4D house to a point where it is congruent with the outside shell of the house, the most optimum structure ensued in terms of invested materials and unit volume of structure. After the war the Beech Aircraft withdrew their support for the production of the house and Fuller began to explore the optimal structural arrangement, developed in the Witchita house, by analysing pure 'tensegrity' systems. With various groups of university students he built a number of tensegrity structures which inspired Fuller's 'discovery' of geodesic domes.

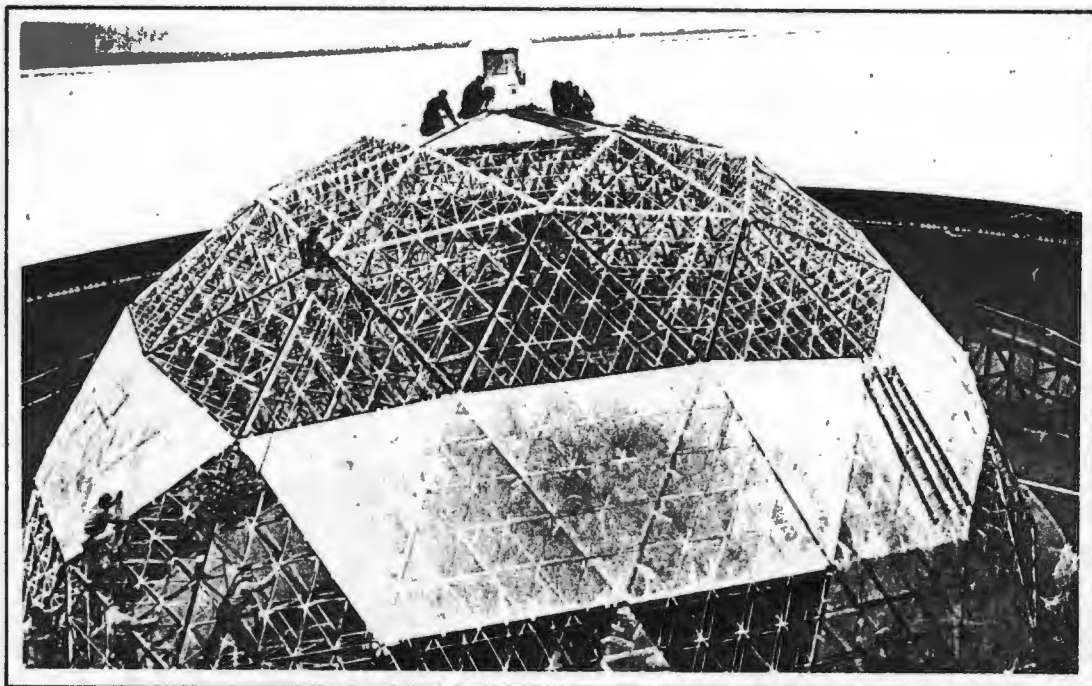
In June 1951 Fuller filed his basic geodesic patent and he began to build experimental structures with the aid of his students. The breakthrough in terms of geodesic structuring came in 1952 when the Ford Motor Company commissioned Fuller to design and construct a 93 ft. (28,36 m) - diameter dome to cover their Dearborn Rotunda Building in Michigan. The dome was built in an octet-truss space frame configuration consisting of two concentric tensegrity spheres, one of lesser radius than the other, and the inner one of one frequency subdivision less than the outer one. Each inner - and each outer - point was interconnected with three outer points and three inner points respectively, resulting in an intertriangulated omnidirectional octet-truss. The success of the Ford-project brought the geodesic dome into the limelight and interest in domes soared.

"It suffices to note that once the Geodesic idea got going it began - as Eugene Field once predicted of Chicago - to make culture hum." (5)

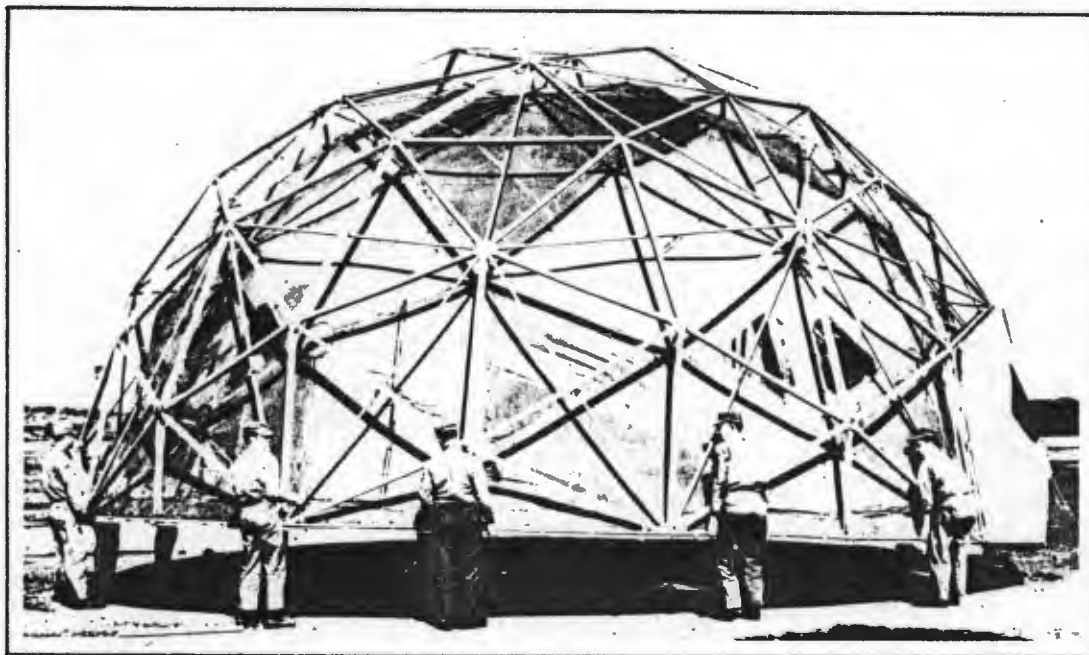
In 1954 Fuller was granted his basic geodesic patent and in the same year he was requested by the United States Marine Corps to advise on mobile



3.6 'Ford dome', Dearborn Rotunda building, 1952



3.7 'Marine Corps Study' dome, 1954

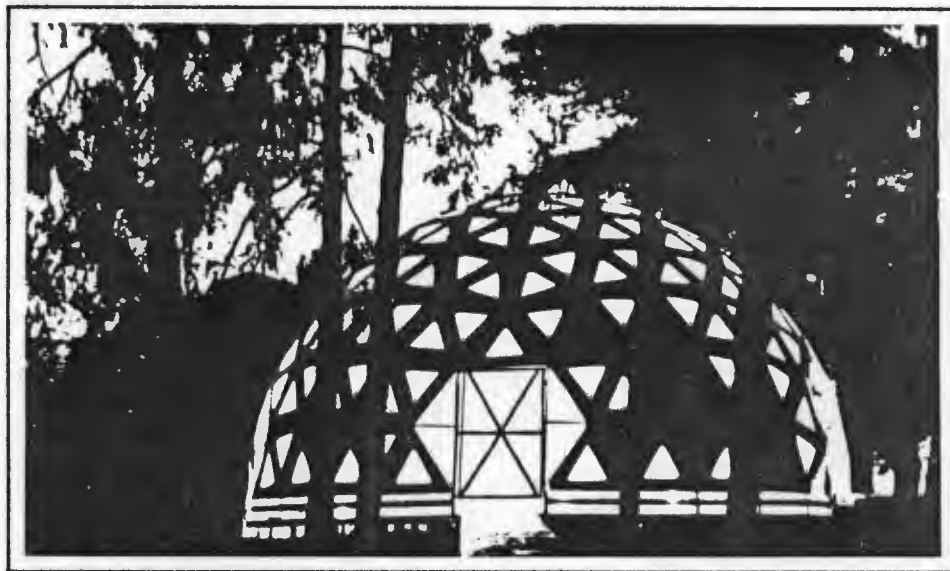


military shelter. One of Fuller's underlying design principles had always been to minimise the weight of a structure to allow for air-transportation in a completely erected state - even his initial multi-deck apartment houses were designed to be transported in completed form by means of a Zeppelin. He believed that air-transportation of completely manufactured dwellings was the optimal method of providing sufficient shelter for mankind. He designed and constructed various domes which were rigorously scrutinised and tested. One of these, known as the 'Kleenex' dome, was made out of corrugated Kraft paper-board. A similar 42 ft. (12,8 m) - diameter paper-board dome won the Triennale 'Gran Premio' (grand prize) at the Tenth International Exposition for Art and Architecture in Milan, Italy, in September 1954. The Marine Corps study revealed stunning information about savings in cost, man-hours, weight and shipping volume achieved by dome shelter relative to the then current shelter solutions. Finally, a 42 ft.-diameter dome of 1/2- and 1/3-sphere configurations was adopted as general replacements for previous mobile military shelter.

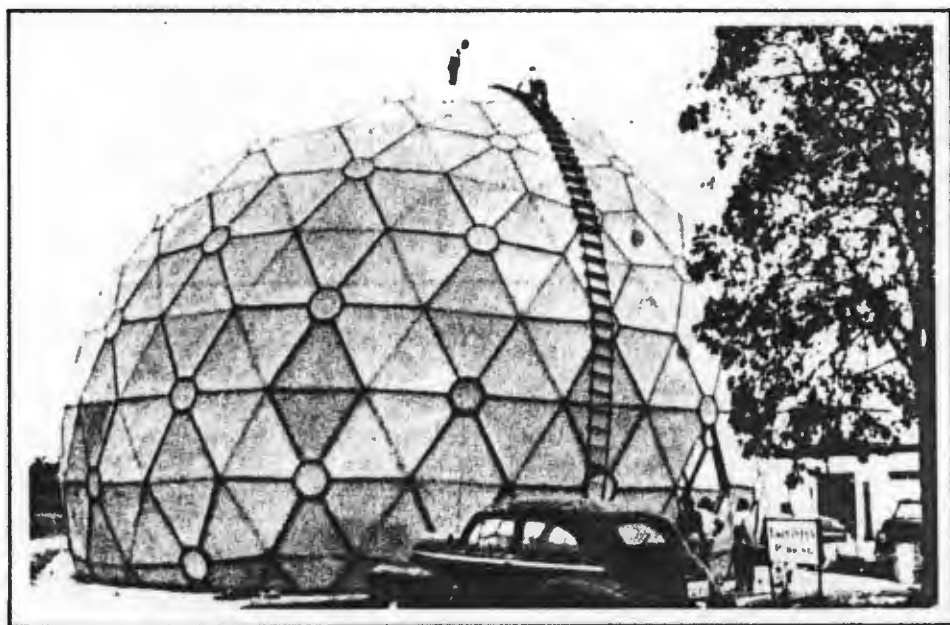
Soon thereafter the United States Air Force commissioned the production of Geodesic Radomes, which were installed as weather-stations along the DEW line in the Arctic circle between Canada and Alaska. The domes, 16,5 m in diameter, made of fibreglass plastic, were assembled on site in fourteen hours and proved to withstand the inherent extremely inclement weather conditions.

In 1956 the United States Department of Commerce decided to erect a geodesic dome at the annual International Trade Fair at Kabul, Afghanistan. This 30 m-diameter clear-spanning dome consisted of 480 aluminium tube struts with a suspended nylon skin and was erected in forty- eight hours by local labour. The dome was the main attraction at

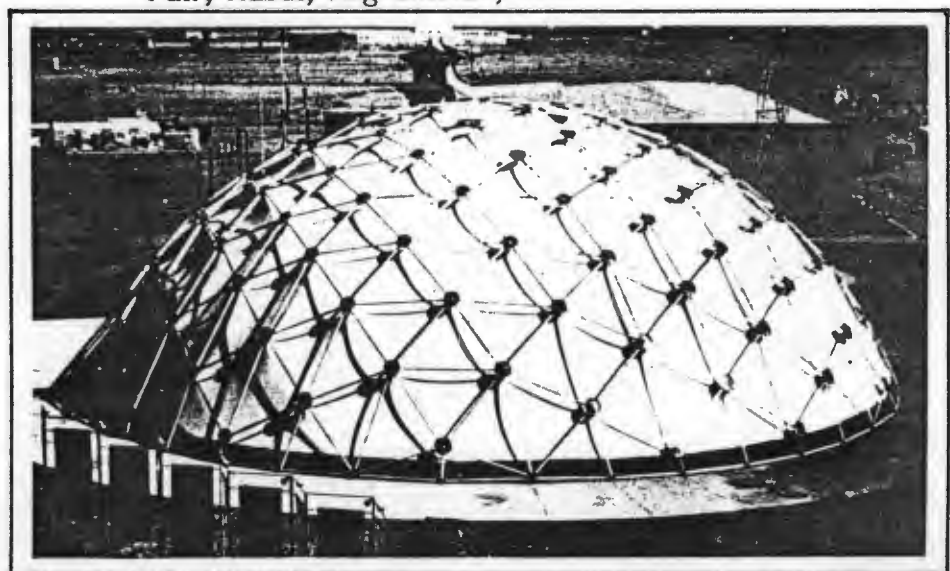
3.8 'Kleenex' paperboard dome, 1954



3.9 Geodesic Radome, 1955



3.10 U.S. Department of Commerce dome at International Trade Fair, Kabul, Afghanistan, 1956

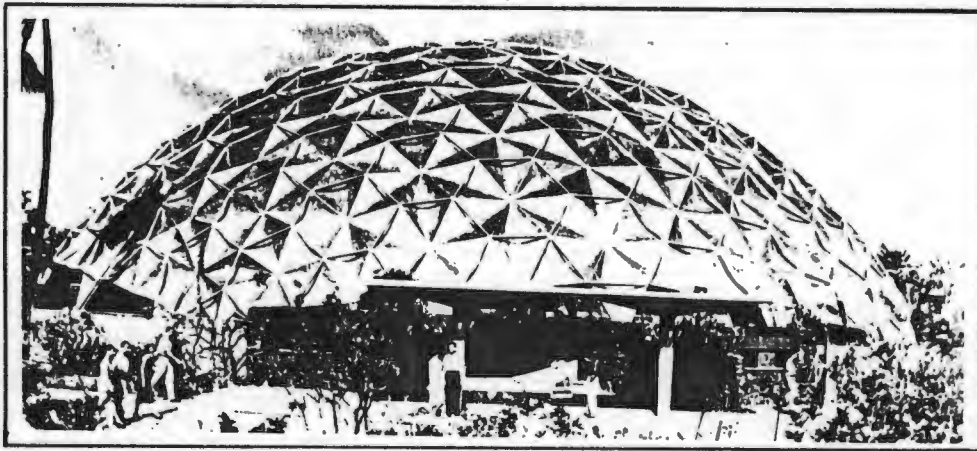


the Fair and the Afghans, who had built it, proudly referred to it as a 'super-yurt', an extension of traditional Mongolian architecture. The same dome was transported by air in disassembled condition to various Trade Fairs around the world.

One of Fuller's first patent licensees was Kaiser Aluminium Company, who in 1958 built a 145 ft. (44 m) - diameter dome at Honolulu in Hawaii. Erection time was twenty-two hours - an hour after completion the Hawaii Symphony Orchestra were having a full-scale concert inside the dome.

In May 1958 Fuller came to South Africa and with senior architecture students from the Universities of Natal and Cape Town he built an 'Indhlu' geodesic dome. On his way to South Africa, Fuller stopped off in Burma where he picked up reputedly the world's oldest known toy, a small ball of interwoven great circle bands of bamboo, called the Burmese toy ball. In South Africa, Fuller became acquainted with the Zulu hut. Inspired by his two recent discoveries, and with a long technical experience of metals, he conceived the idea of the 'Indhlu' geodesic dome made out of corrugated aluminium sheets. The design was a development of the geodesic plydomes which Fuller had patented in 1957, made out of standard plywood sheets, bent and joined in such a way as to form a spherical structure. The corrugated aluminium sheets of the 'Indhlu' dome formed five interwoven great circle arches, with a complete great circle band of sheets around the base of the dome to serve as a tensional bracing buttress (see 5.4.1.2 : Figure 5.6). The detailed working drawings on weaving panels together were filed as part of Fuller's 'Laminar Geodesic Dome' patent in May 1960.

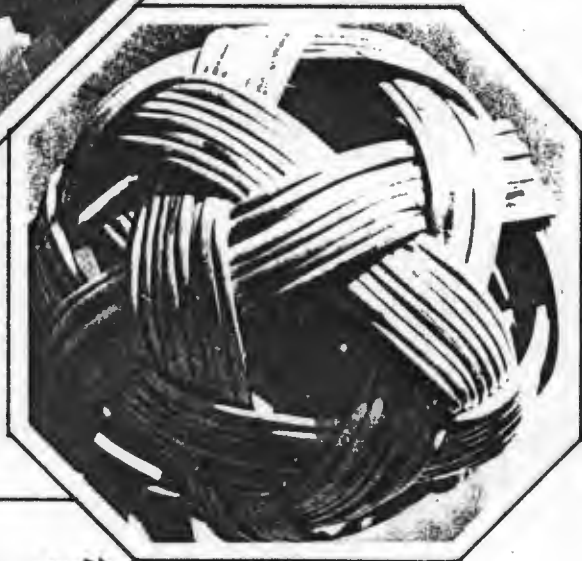
Also in 1958 Fuller's patent licensee, North American Aviation, built a



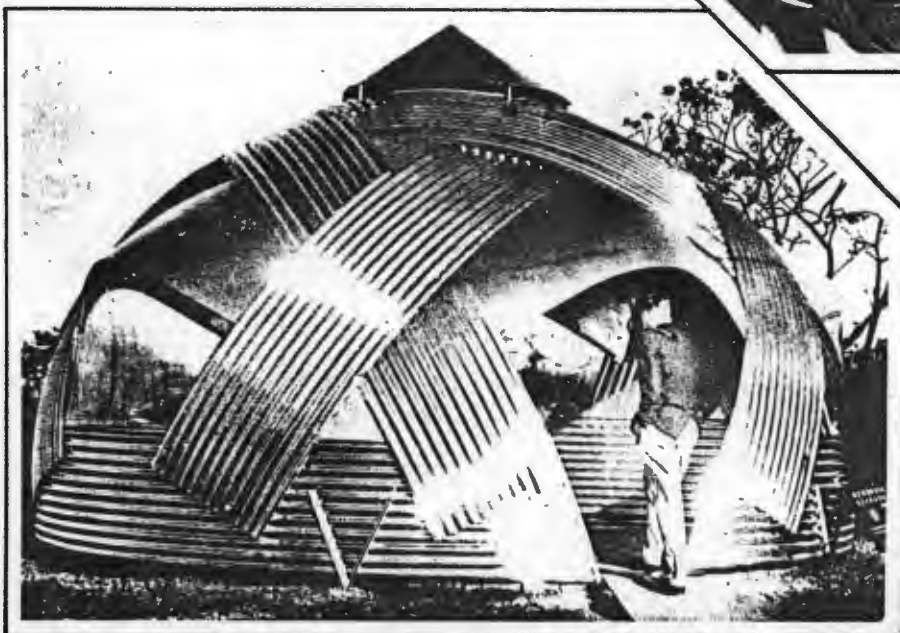
3.12 Geodesic Plydome, 1957



3.13 Burmese toy ball



3.14 'Indhlu' Geodesic dome, 1958





265 ft. (80 m) - diameter dome in Cleveland, Ohio. In 1959 another licensee, the Union Tank Car Company put up a dome 384 ft. (117 m) in diameter at Baton Rouge, Louisiana and later another similar dome at Woodriver, Illinois. They were then the largest clear-spanning enclosures ever constructed, being large enough to 'cover a full American football field with its end zones, a running track around it, with room for generous circular-segment grandstands on either side of the field and track'.<sup>6</sup>

Later that year, Kaiser Aluminium Company built a 200 ft. (61 m) - diameter dome as the United States National exhibit in Moscow. The Russians purchased the dome with the intention of using the same geodesic principle in some of their future, very large enclosures.

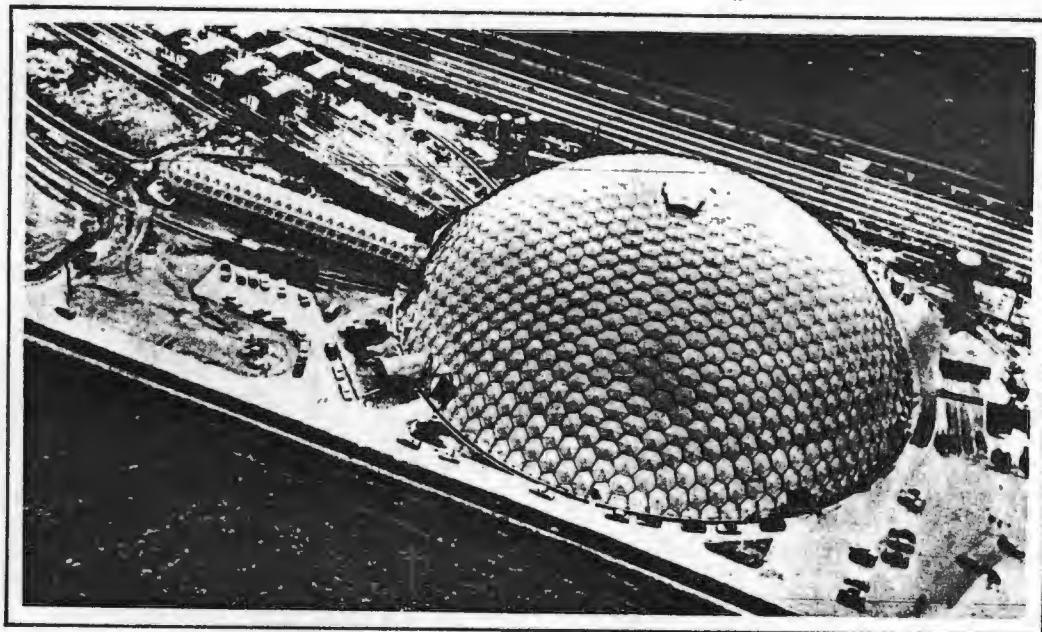
By this stage Fuller was building more experimental 'tensegrity' structures with groups of university students, notably a 72 ft. (22 m) - diameter three-quarter-sphere 'basketry tensegrity' structure at Southern Illinois University. In August 1959 Fuller's 'Tensile-Integrity Structures' patent was filed.

By the turn of the decade Fuller was beginning to build new mathematical structures by developing the octet-truss space-frame system based on his 'Synergetic Building Construction' patent which had been filed in February 1956.

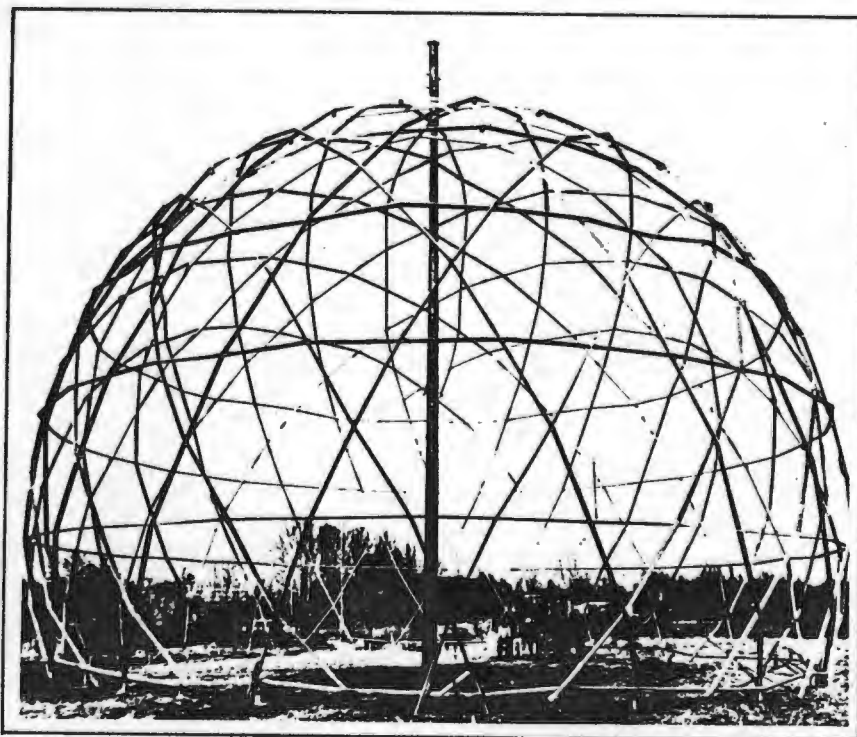
In 1961 the 'Geospace' foam-core paperboard dome, a mass-produced 22 ft. (6,7 m) - diameter dome was manufactured by the Monsanto Chemical Company and installed by the United States Peace Corps as emergency shelter in Puerto Rico.

By 1964 Fuller had over 125 patent licensees who had collectively built about 3000 geodesic structures in 50 countries around the world. The

3.15 Union Tank Car Co. dome, Baton Rouge, Louisiana, 1959



3.16 'Basketry Tensegrity' structure, 1960



3.17 'Geospace' foam-core paperboard dome, 1961





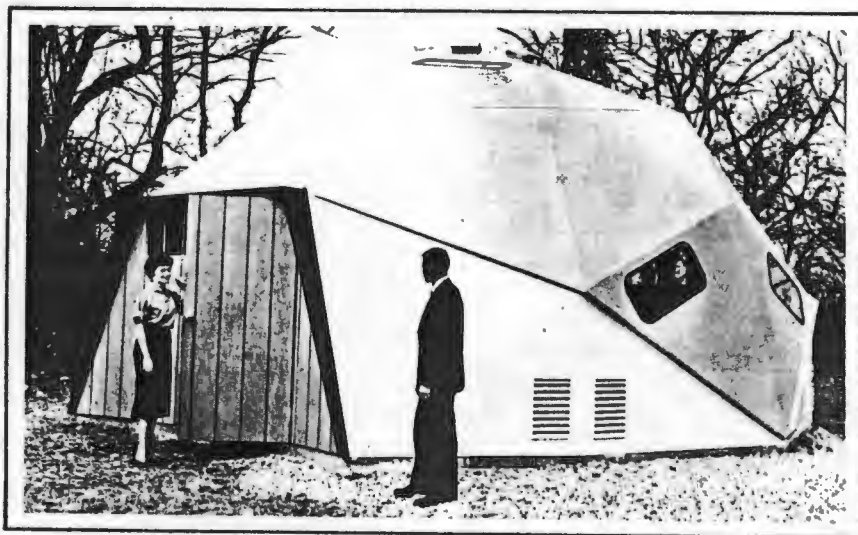
most successful geodesic housing enterprise at that stage was the Pease Woodwork Company, Ohio, who manufactured the 'Peasedome', a 26 ft. (8 m) - diameter, wood frame, plywood sheet dome.

In 1965 an enterprising group of university students founded Drop City on the outskirts of Trinidad, Colorado. They were the first American dome community, building from the discards of a wasteful society and later becoming a stop-off point for hundreds of hitch-hikers travelling across country to Haight Asbury. The young revolutionary American hippies of the late sixties saw the dome as the physical expression of their revolution against society, the embodiment of their free-thinking culture '... corners constrict the mind. Domes break into new dimensions ...'.<sup>7</sup> Fuller gave Drop City the 1966 Dymaxion Award for 'poetically economic structural accomplishments'.

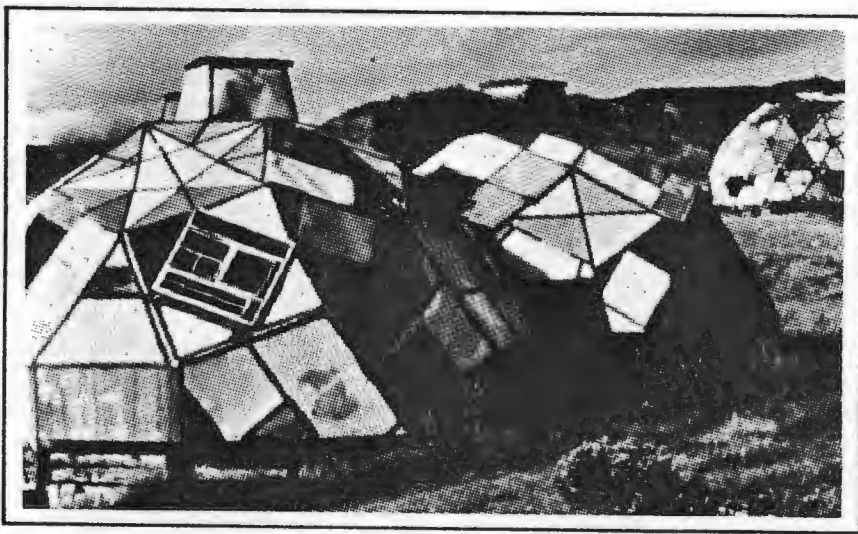
In 1967 probably the most impressive geodesic dome ever was built as the American Pavilion at the Canadian Universal and International Exhibition, EXPO '67, in Montreal. The 3/4-sphere dome, 250 ft. (76,2 m) in diameter, was constructed in a space-frame configuration by one of Fuller's companies, Fuller and Sadao Inc. in conjunction with one of his licensees, Geometric Inc. Associated Architects.

Between 1969 and 1971 seventeen geodesic domes were constructed at the Pacific High School in California's Santa Cruz mountains. Domebook 2, the most comprehensive manual on practical dome construction, was written and compiled by these students and published in 1971. Besides their own recorded experiences in dome construction, the book contains feedback from various other dome-builders responding to Domebook 1. The editor, Lloyd Khan, has been referred to as the 'Pied Piper of Domedom'.<sup>8</sup> His meticulous academic approach to the analysis and

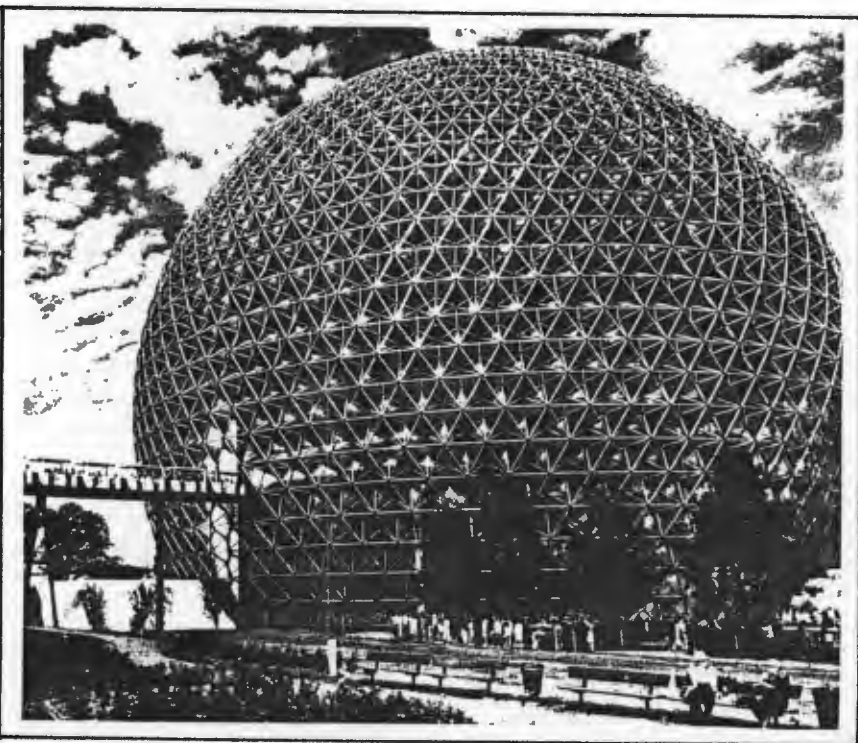
3.18 'Peasedome'



3.19 'Drop City', 1965-1970



3.20 'EXPO '67' dome, Montreal



general study of practical dome construction has offered great insight into the inherent problems associated with geodesic structuring. He has seen, felt and recorded the euphoric successes and the disheartening failures of practical dome construction - his writings and publications must therefore lie at the heart of any study on geodesic dome construction.

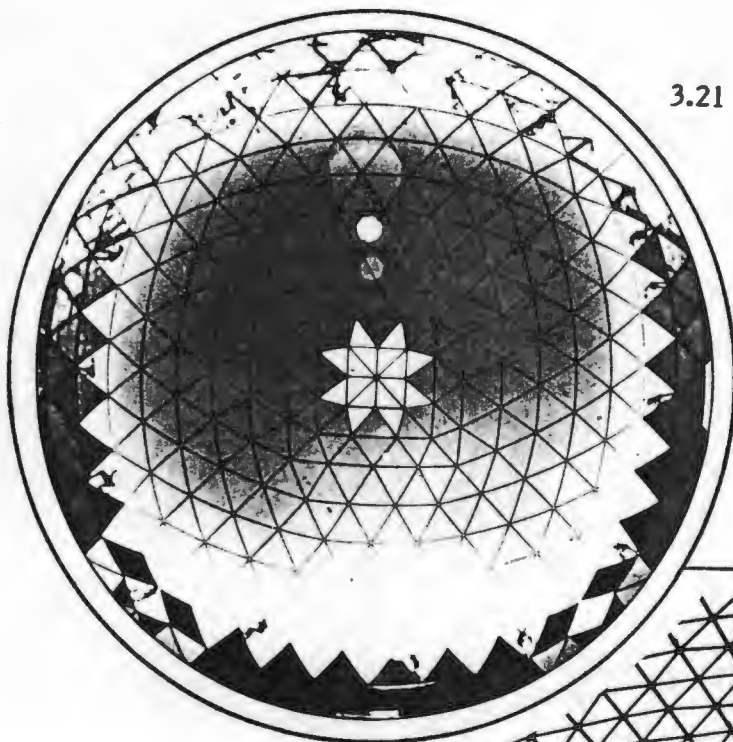
By this time two competent and successful commercial companies were manufacturing domes for the residential market: Bill Wood's 'Dyna Dome's and Steve Baer's 'Zomeworks', both of which are today still successfully competitive in the American residential housing market, although Baer is now exclusively designing solar heating systems and other utilities for the development of autonomous housing.

Over the next decade hundreds of domes were built all over the world, ranging from cheap mass-produced 'kit-form' shelter through to exclusive one-off residential dwellings, to large clear-spanning industrial and commercial structures. At present there are over 150 commercial enterprises in the United States of America alone which are engaged in the construction of geodesic dome structures. For the purposes of this study, twenty-seven of these companies were contacted by post. Judging by the response, the geodesic dome market is far from extinction, as is often assumed - there are still many enthusiastic individuals, and groups, who are challenging the 'squares' and 'blockheads' of modern society.

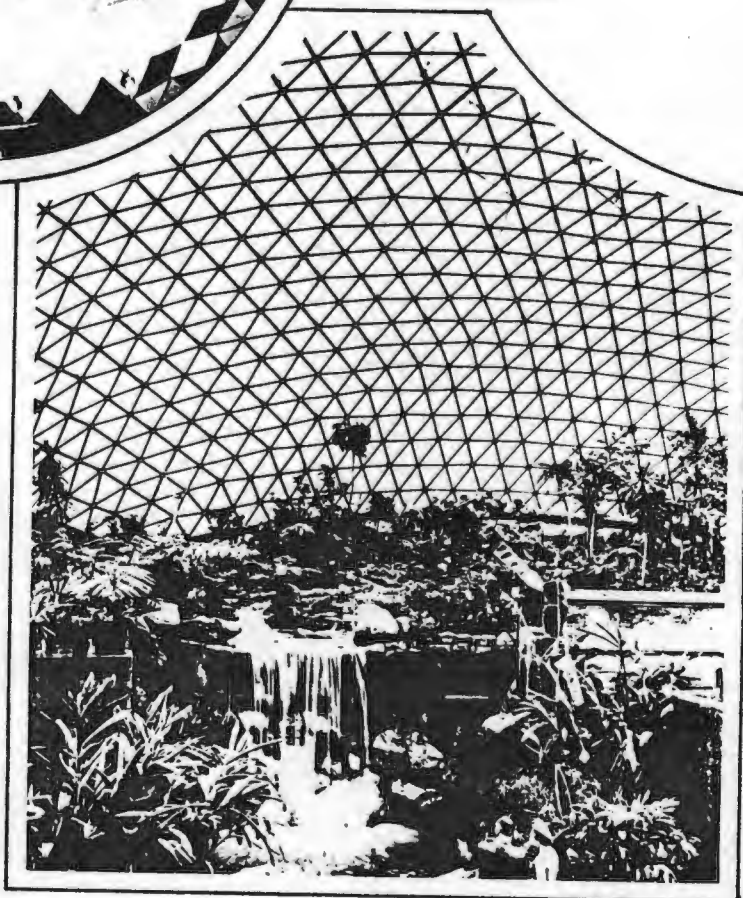
Last year, at the age of 88 years, Fuller passed away peacefully - he will undoubtedly be remembered as one of the greatest thinkers of our time. A man who not only developed revolutionary concepts of structure, but who applied his thinking to achieve the technologically most innovative ways of bettering human existence on earth.

Fuller's initial conception of the geodesic dome as a form of mass-pro-

3.21 Dyna dome



3.22 Climatron



3.23 'Temcor' dome, California



duced, industrialised, autonomous, low-cost shelter did not materialise as planned, largely because Fuller himself feared the capitalistic exploitation of his concept. His patents are so well tied up that commercial enterprises have found it extremely difficult to evade their firm claws. However Fuller always spoke of a time lapse of 25 years between the inception of an idea and some form of commercial practical application thereof. In 1958 he concluded that the geodesic dome shelter was ideally suited to mass-produced housing for southern Africa's black population - the time has now arrived for this proposition to be developed and put into practice.

### 3.24 Richard Buckminster Fuller





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## CHAPTER FOUR

This section must be read in conjunction with Appendix B

### 4. THE GEODESIC DOME: METHODS OF CONSTRUCTION

#### 4.1 Introduction

The basic structural framework of all geodesic domes defines an array of triangular facets which roughly approximates a sphere. The larger the structure, the more complex the array of triangles generally is and the more closely the structure resembles a sphere. This combination of the triangle, the only inherently stable structural configuration, and of the sphere with its inherent structural and environmental advantages (see Chapter 7), makes the geodesic dome the strongest, most efficient building system probably ever devised.

The principal polyhedron from which the design of most geodesic domes is derived, is the icosahedron, which is a 'platonic' polyhedron defining twenty equal triangular facets. It approximates a sphere more closely than the tetrahedron and the octahedron, which are the only two other platonic polyhedra with triangular facets. Each triangular facet of the icosahedron is too large and cumbersome when constructed on the scale of a full-size dwelling unit - thus each facet is subdivided into smaller triangles to remain within structural fabrication and erection limits. Each icsa-edge is frequency modulated, and points of subdivision are projected



onto a circumscribed sphere. As the frequency of subdivision increases, the structure becomes more spherical and consequently stronger, until an edge-frequency of sixteen subdivisions is reached, at which stage the edge is assumed to coincide with the arc of a sphere. As the points of subdivision are all points on the surface of a common sphere, they can be interconnected with a three-way grid of great circles, thus forming a structure in which all chords are in geodesic alignment. The points of subdivision are derived either by means of analytical geometry or by spherical trigonometry, both resulting in sets of 'chord factors' which, when multiplied by the radius of the proposed dome, give the lengths of various chords or struts (see Appendix B).

## 4.2 Types of Domes

Geodesic dome construction can be broadly classified into two distinct groups:

- Strut-and-Skin domes
- Panel domes.

### 4.2.1 Strut-and-Skin Domes

As the name suggests these domes consist of distinctly separate structural framing elements which, once erected, are covered with flat sheet cladding elements. The framework consists of a triangular network of struts, which are connected to each other by means of hubs. The struts are arranged in space in geodesic alignment - thus all hubs are points on the surface of a common sphere. They represent the vertexes of the triangles defined by the network of struts, which in turn represent the edges of the same triangular network. The twelve vertexes of the

principal icosahedron are called 'icosacaps' and are represented by hubs which connect the ends of five incoming struts. All other hubs connect six struts together - the vertexes they represent are a direct result of the modular frequency subdivision of the principal icoso-edges.

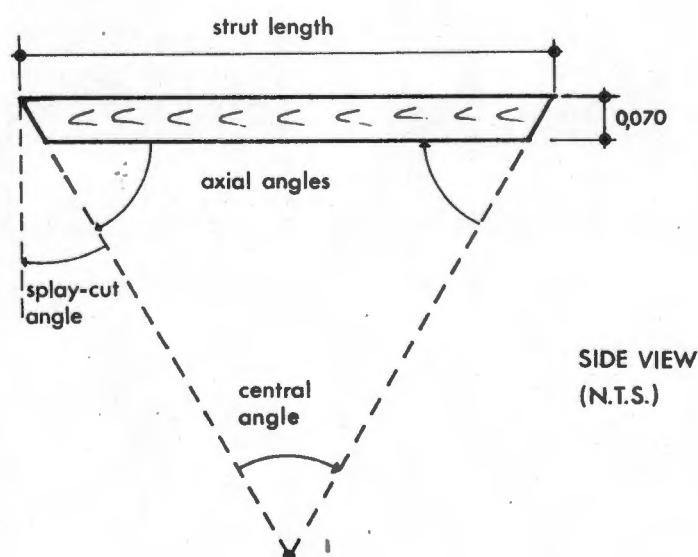
#### 4.2.1.1 Strut Details

Struts used in the context of this study are of timber, but metal struts may be alternatively used where timber is deemed to be unsuitable. For 'Strut-and-Skin' domes all struts are ex - 50x76 mm sawn S.A. Pine - they are planed on all sides to give an effective cross-sectional area of 44x70 mm.

Strut lengths, calculated by multiplying the relevant chord factors by the radius of the dome (see Appendix B.5), extend from one vertex to another. Thus, if hubs are used, each strut must be shortened by the diameter of the hub, i.e. by the radius at each end. Once struts are of correct length (to the nearest mm), each one is angle-cut in three stages:

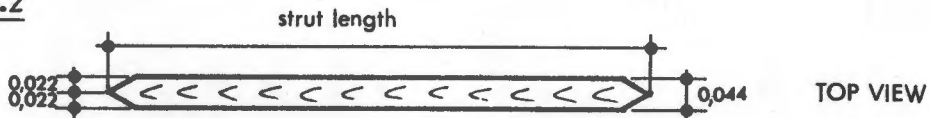
- Splay-cut (once at each end):  $90^\circ$  minus Axial Angle.

Figure 4.1



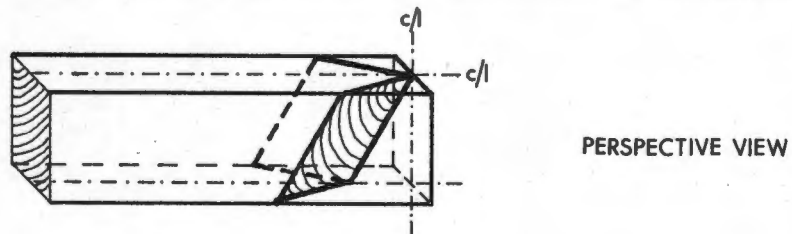
- Mitre-cut (twice at each end):  $90^\circ$  minus  $\frac{1}{2}$  Face Angle.

Figure 4.2



NOTE: 'Mitre-cuts' must follow 'Splay-cuts', because angles are compounded - a jig may be set up to cut compound angles in one cut.

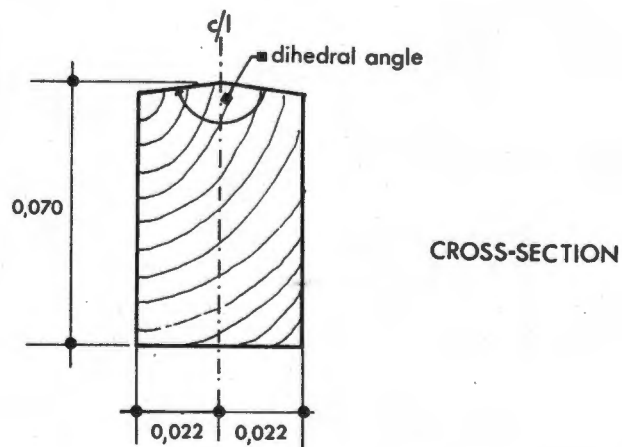
Figure 4.3



- Bevel-cut (twice along top edge):  $\frac{1}{2}$  ( $180^\circ$  minus Dihedral Angle).

'Ripping' may not be necessary - this depends on the method of cladding.

Figure 4.4



Angle-cutting of struts is extremely time-consuming and accuracy is of utmost importance - a radial arm saw simplifies the process. The cutting-table must have a 'fence' and a 'stop table mark' so that struts can be held accurately and firmly in position while cutting. Each strut is checked against a 'master strut' to ensure accuracy. Struts are now colour-coded and stacked in respective piles.

#### 4.2.1.2 Hub Systems

Various methods of hub connections for timber struts have been devised, of which the following seem most practical.

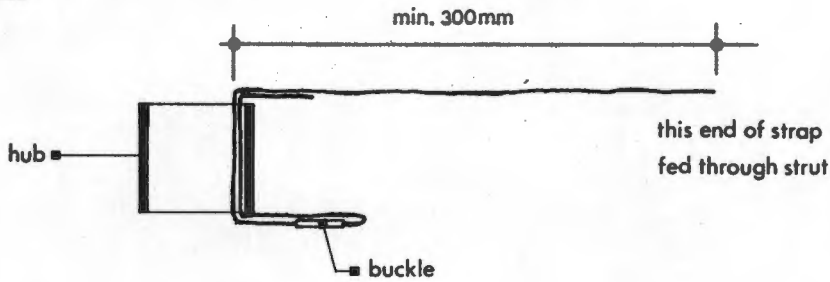
- Tube and strap
- Exposed washer (or plate)
- Concealed washer (or plate)
- 'Fixed axial angle' tube and channel
- 'Fixed axial angle' plate
- 'Fixed face angle' steel strap
- Flexible flat hub

##### 4.2.1.2.1 Tube and Strap Hub

This hub system was originally probably the most widely used connection, being a relatively cheap and simple system. Struts only need to be 'splay-cut' and 'bevel-cut', but not 'mitre-cut'. They are fixed to a 75 mm-diameter (outside dimension) steel (or PVC) tube, 70 mm long, by means of a 12 mm wide galvanised steel (or hoop iron) strap and a buckle. Each strut length is shortened by 75 mm to accommodate the cylindrical hub. A 12 mm-diameter hole is drilled approximately 100 mm from both ends of each strut to take the hoop iron strap. However accuracy in drilling is not of vital importance relative to other hub systems, which employ fixing bolts instead of straps, and require absolute accuracy in drilling strut-holes.

Each strap, 600 mm long, receives a fixing buckle, is then bent to the required shape and is hooked over the hub (see Figure 4.5).

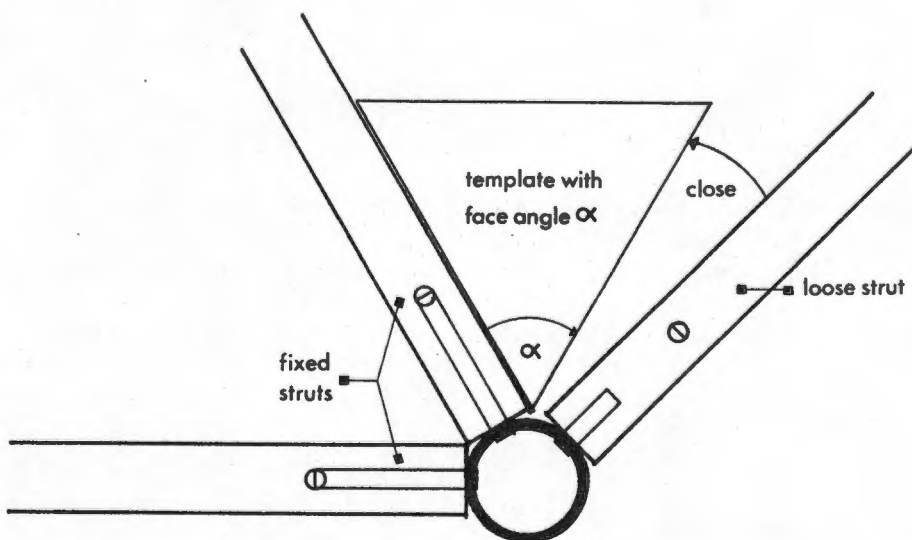
Figure 4.5



Before the strap is fed through the strut-hole, a 12 mm-diameter half-round is placed inside the hole to support the strap and to prevent it from cutting into the strut, which would result in the dome sagging over time. The loose strap end is again slipped through the buckle and is tightened by cranking with a special 'strapper'. Finally the buckle is crimped to securely fix the strap. Note that the buckle is positioned on the inside edge of the strut so that it does not interfere when cladding panels are fixed.

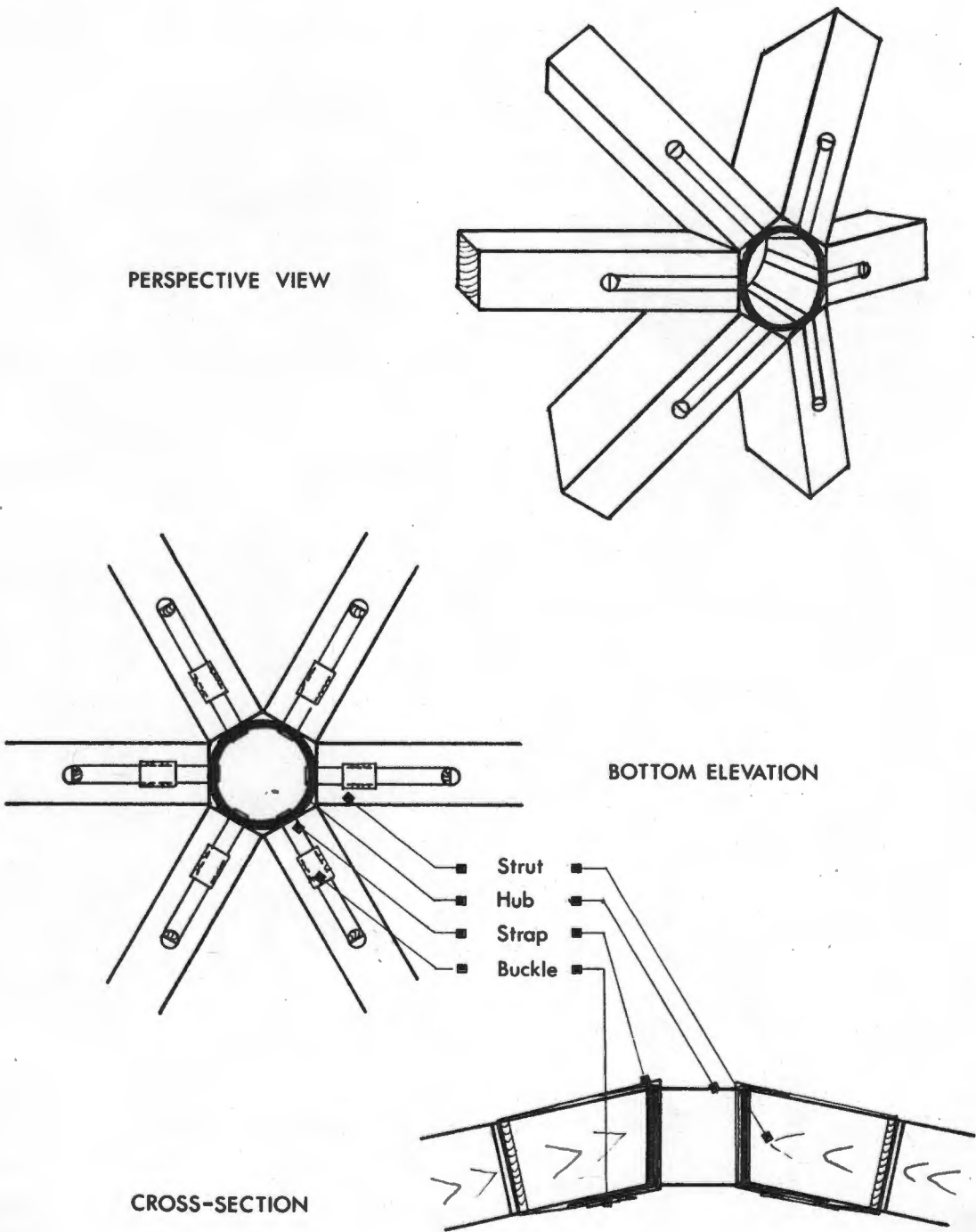
In order to fix struts at the correct 'face angle' around the tube hub, a template should be used. The strap is tightened and crimped after the loose strut has been closed in against the template.

Figure 4.6



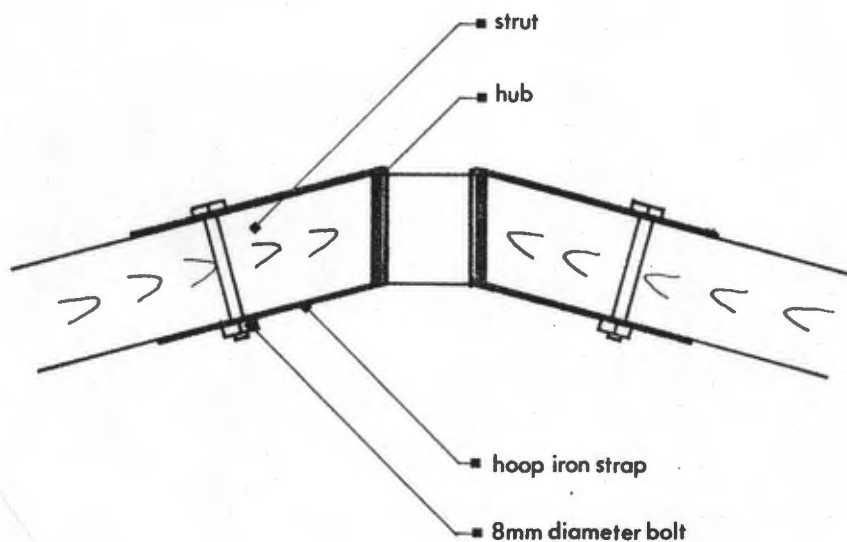
Note that the size of the tube must allow exactly six struts to be fitted around the hub - or five struts at the 'icosacaps'. Thus for 44 mm wide struts the outside diameter of the tube is 75 mm and 60 mm respectively. Larger hubs will allow struts to slide around until the cladding has been fixed.

Figure 4.7 Tube and Strap Hub - Details



The process of strapping introduces a relatively skilled on-site operation as compared to bolting. Also a special 'strapper' and a 'crimper' are required, which adds to the cost of the system. Possibly a more economical system would be to use 40 mm wide hoop iron straps bolted onto struts as follows:

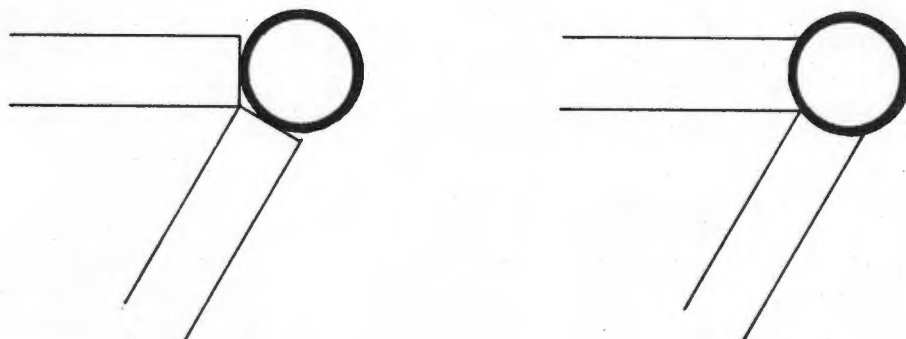
Figure 4.8



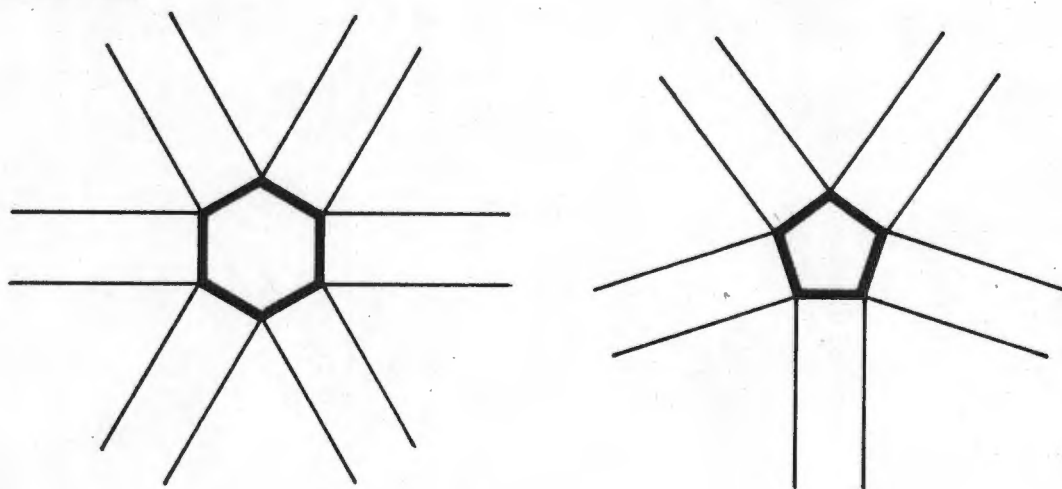
The bolts can however not be countersunk into struts - thus their projection beyond the edges of the struts induces a problem with cladding. Nailing instead of bolting may suffice.

Strapping is not as strong and sturdy as bolting, unless executed by an experienced and meticulous operator - especially since each strut only touches the hub at one point, unless ends of struts are cut concave - this is however a difficult and costly operation.



Figure 4.9

Alternatively hexagonal and pentagonal hubs may be used instead of cylindrical tubes.

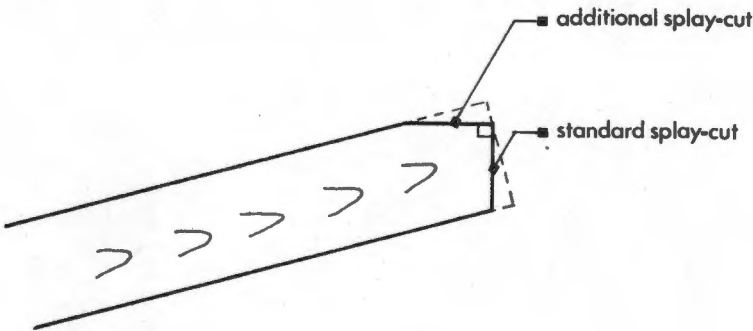
Figure 4.10

#### 4.2.1.2.2 Exposed Washer or Plate Hub

This is another hub system which has been extensively used in dome construction. The plate hub is either of 5 mm steel (150 mm-diameter) or 15 mm plywood (200 mm-diameter) or 15 mm FRC (250 mm-diameter) whichever is most suited to the overall design of the structure.

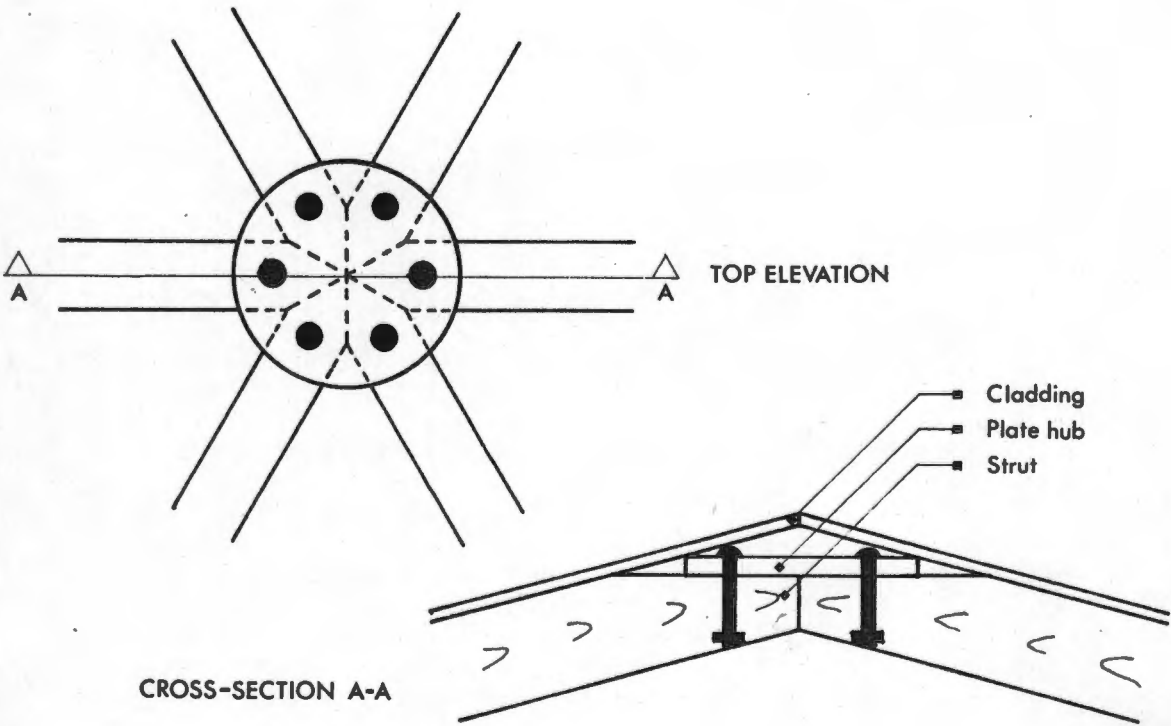
Besides the three standard angle-cuts, each strut requires an additional splay-cut (at both ends) to allow plates to sit flat on struts. The angle of the additional cut is the same as for the standard splay-cut.

Figure 4.11



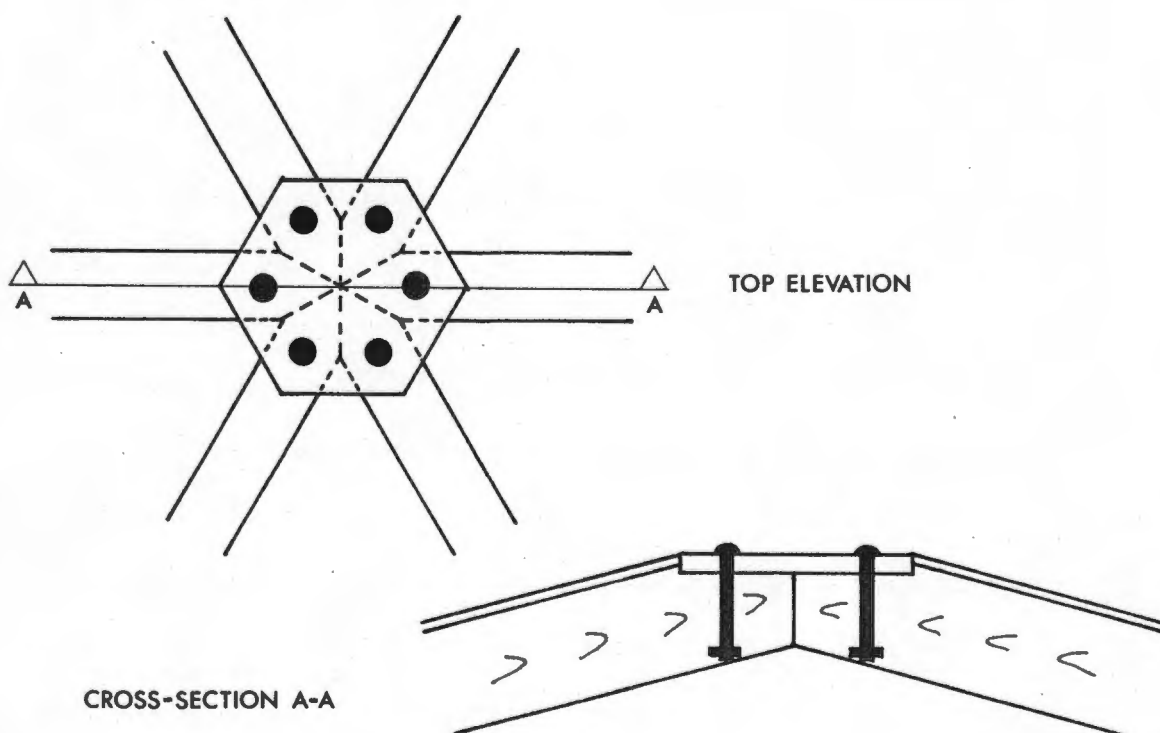
The drilling of plates and struts must be extremely accurately executed in order to ensure perfect alignment of holes for bolts during erection. All holes and bolts are 8 mm-diameter, thus allowing for no margin of error. Some bolts will have to be driven home firmly, resulting in tight-fitting, sturdy connections.

Figure 4.12



Instead of using circular plates or washers, it may be preferable to use hexagonal and pentagonal plates, which may perform part of the cladding function as well as securing strut ends. There are two main reasons for using the plate hub as an infill cladding element; firstly, the size of a dome of a particular design is limited by the standard dimensions of various cladding elements (see 4.2.1.3) - by using the plate as an infill cladding element, the maximum size of the structure can thus be increased. A 3-frequency alternate dome, for example, can be increased from a maximum diameter of 6,8 m to a structure 7,3 m in diameter - this increases the floor area from 35 m<sup>2</sup> to 43 m<sup>2</sup>. The second major reason for using the plate hub as an infill cladding element is that the vertexes of the dome become slightly truncated, thus eliminating the possibility of the waterproofing bandage being punctured by the sharp vertexes of an untruncated structure.

Figure 4.13



It must be carefully noted that, because the hub is a flat plate and perpendicular to the radius of the dome, the sum of the face angles around any one hub must equal exactly  $360^\circ$ . The facets of the dome however meet at an angle at their vertexes and the face angles are a function of their axial angles - thus the sum of their face angles around any one vertex is less than  $360^\circ$ . This phenomenon is only really significant if there are different face angles around a hub, because if all angles are equal, then angles are calculated by simply dividing  $360^\circ$  by the number of angles. Thus a regular 'Hex' hub or 'Sixer' has six  $60^\circ$  angles and a regular 'Pent' hub or 'Fiver' has five  $72^\circ$  angles. Some 'Hex' hubs are however not regular, being surrounded by a number of different face angles. The 'hub face angles' are calculated by adjusting the 'actual face angles' proportionately to add up to  $360^\circ$ .

Taking the 3-frequency alternate design as an example - there are two types of 'Hex' hubs and one 'Pent' hub. The 'Pent' hub is surrounded by five equal face angles of  $70,73^\circ$ , measured across each angularly-orientated facet of the dome. The hub itself, being flat, defines five equal face angles of  $72^\circ$ . One of the 'Hex' hubs is surrounded by equal face angles of  $58,58^\circ$ , but inherently the flat hub defines six equal face angles of  $60^\circ$ . The other 'Hex' hub is surrounded by two different face angles, four angles of  $60,71^\circ$  and two of  $54,63^\circ$ . The hub is accordingly adjusted to define four face angles of  $62^\circ$  and two angles of  $56^\circ$ .

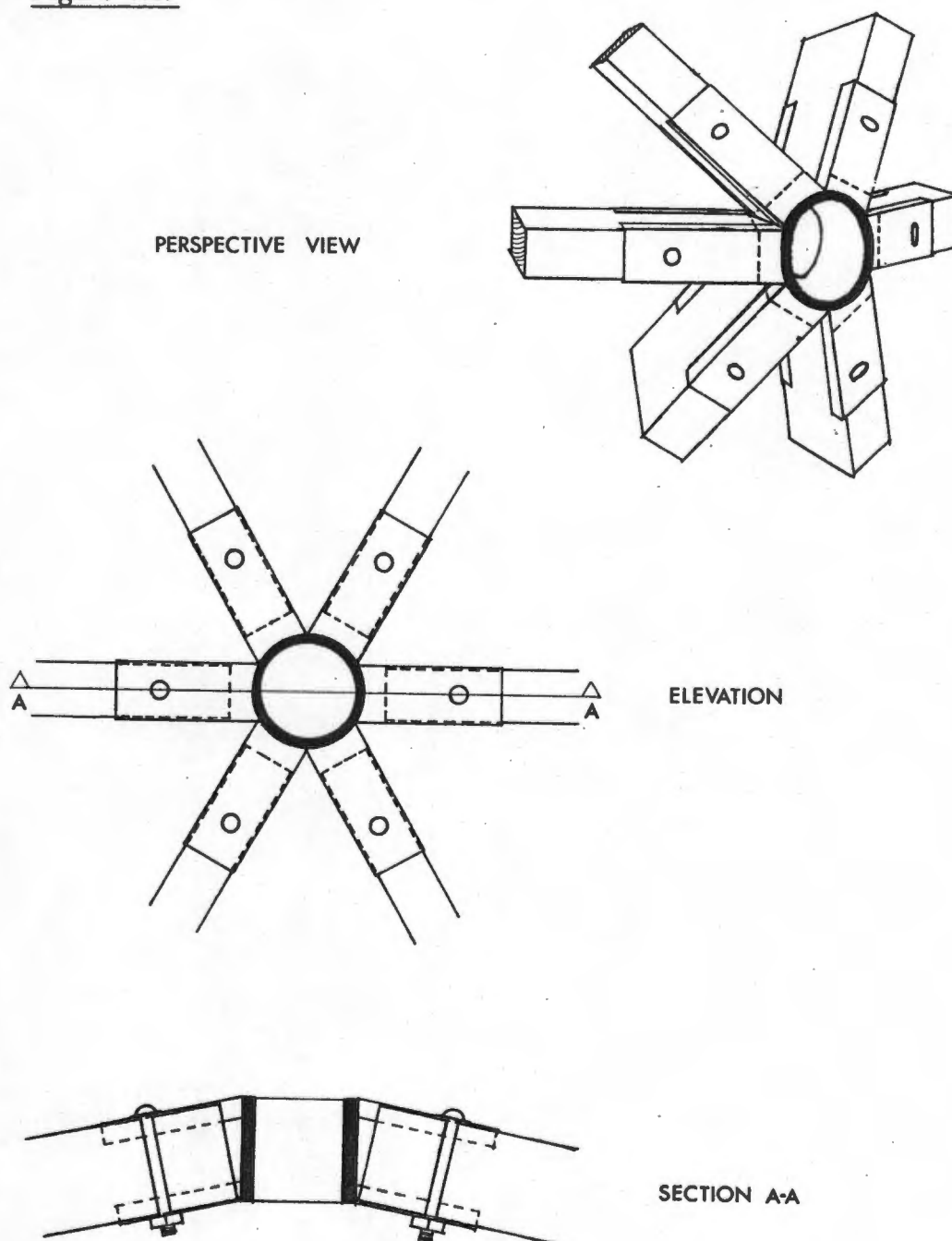
**NOTE:** The discrepancy between 'actual face angles' and 'hub face angles' are naturally eliminated when the dome takes on its arcuate form.



#### 4.2.1.2.4 'Fixed Axial Angle' Tube and Channel Hub

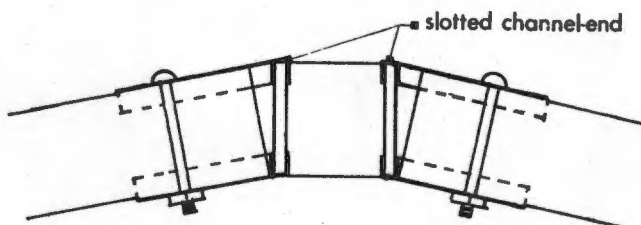
This hub system is very accurate and strong and simple to use on site. The cutting of struts is minimised, with no angle-cuts required. Drilling of bolt-holes must be very accurately executed, as must the process of welding channels to the tube-hubs at the correct axial - and face - angles.

Figure 4.17



Instead of welding channels, they may be slotted onto the tube-hub.

Figure 4.18



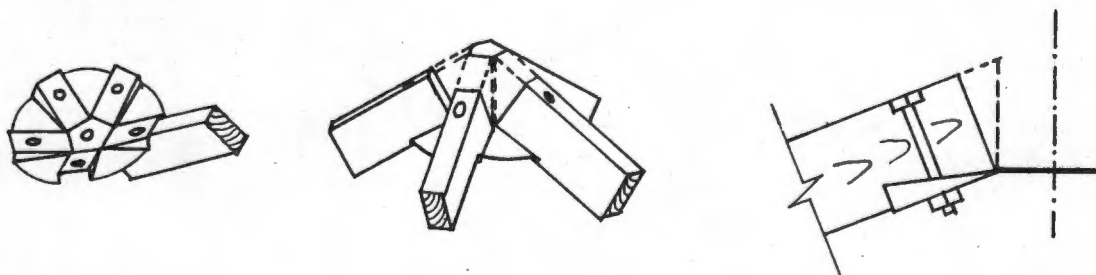
The loose slotted channels are only securely fixed onto the hub when the bolts, fixing the struts, are tightened. The correct face angles between struts are determined by means of a template before bolts are tightened, as with the 'tube and strap' hub.

An alternative to cylindrical tube-hub are hexagonal and pentagonal tubes, which allow for square cutting of channel ends instead of concave cutting.

#### 4.2.1.2.5 'Fixed Axial Angle' Plate Hub

A 2 mm thick steel plate, 150 mm in diameter, can be pressed into 'Fiveway Plates' or 'Sixway Plates' in such a way that the axial angle of each incoming strut is fixed accurately while channels are pressed into the plate to guide struts at the correct face angles. Each strut is fixed onto the plate with one 8 mm-diameter, 75 mm long bolt.

Figure 4.19



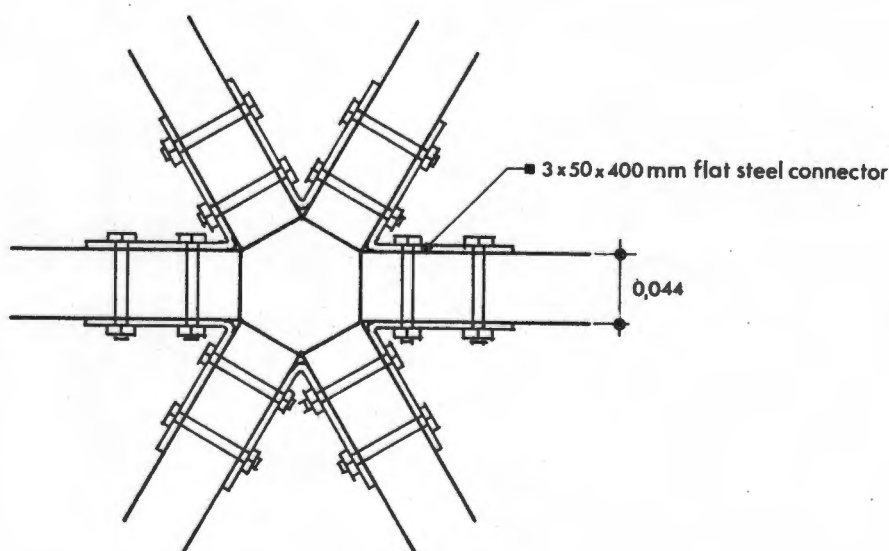


If, as the manufacturers (a British concern with an outlet in South Africa) maintain, these plate hubs do provide accurate angles, this is probably the easiest, neatest and most efficient hub-system yet devised. As with the 'tube and channel' hub, the angle-cutting of struts is eliminated (besides possible 'ripping'), but the drilling of bolt-holes must be accurately executed so that exact strut lengths are achieved.

#### 4.2.1.2.6 'Fixed Face Angle' Steel Strap

3x50 mm flat steel shared connectors, 400 mm long, are bent to the required face angles. Struts need not necessarily be angle-cut - face angles are determined by the connectors, thus no mitre-cutting is required; splay-cuts are not essential, as struts will inherently take up the required axial angles once all struts are fixed. Connectors and struts must be accurately drilled for alignment of bolt-holes.

Figure 4.20



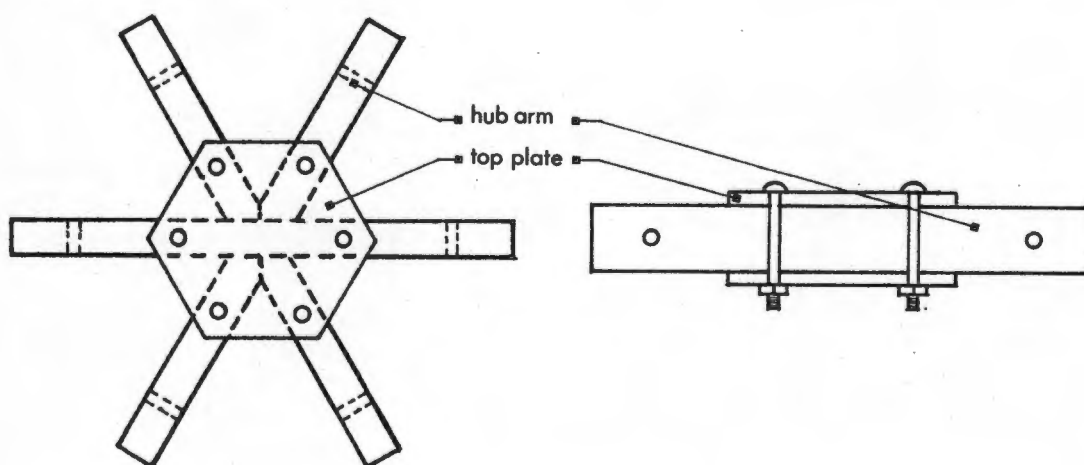
It is recommended that the complete framework is assembled by inserting and fixing only one bolt per strut-end - at this stage the structure is still 'flexible' (see 4.2.1.2.7). Then all other bolts (or dowels) are inserted and tightened to stabilise each connection.

#### 4.2.1.2.7 Flexible Flat Hub

These hubs are manufactured as follows:

Flat plates (two per hub - a top plate and a bottom plate) are drilled in alignment with face angles as before (see 4.2.1.2.2). Plates are preferably hexagonal and pentagonal instead of circular. 44x70 mm 'hub-arms' are cut to length and fixed with 8 mm-diameter bolts between the two identical plates. The required face angles between hub-arms are achieved by aligning pre-drilled holes in plates - a template should be used to check that all angles are accurate (see 4.2.1.2.1).

Figure 4.21



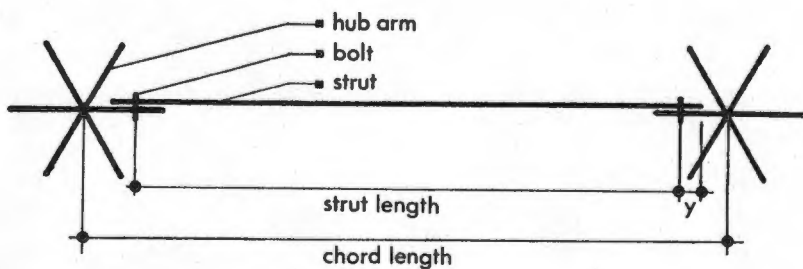
This hub system differs from the previous ones in two major respects:

- It is a 'flexible' hub - this means that the structure only 'locks' into position when the last strut is fixed. During assembly bolts must therefore not be fully tightened until the framework is complete. The framework is inherently unstable during assembly as the flexibility of the hubs allows struts to rotate until they are fixed. This freedom to rotate eliminates any leverage from working against the joint. With rigid hubs there is a leverage of approximately 1,4 m (length of strut) working against the joint, often

resulting in struts splitting or hubs breaking. The flexible hubs allow all struts to naturally lock into position in alignment with chords subtending the required central angle - thus splay-cutting of strut ends is not necessary because the required axial angles are automatically determined. It is however of utmost importance that all struts are cut exactly to length, measured from the centre to centre of hubs minus the radius of the hub at each end.

Besides accurate cutting to length, the drilling of bolt-holes is of major importance. Being a flexible joint, the position of bolts creates a pivot-point which must be absolutely accurately positioned so that the exact chord lengths and axial angles are achieved. In calculating lengths of struts and hub-arms, the position of the bolts defines the division line between strut and hub.

Figure 4.22

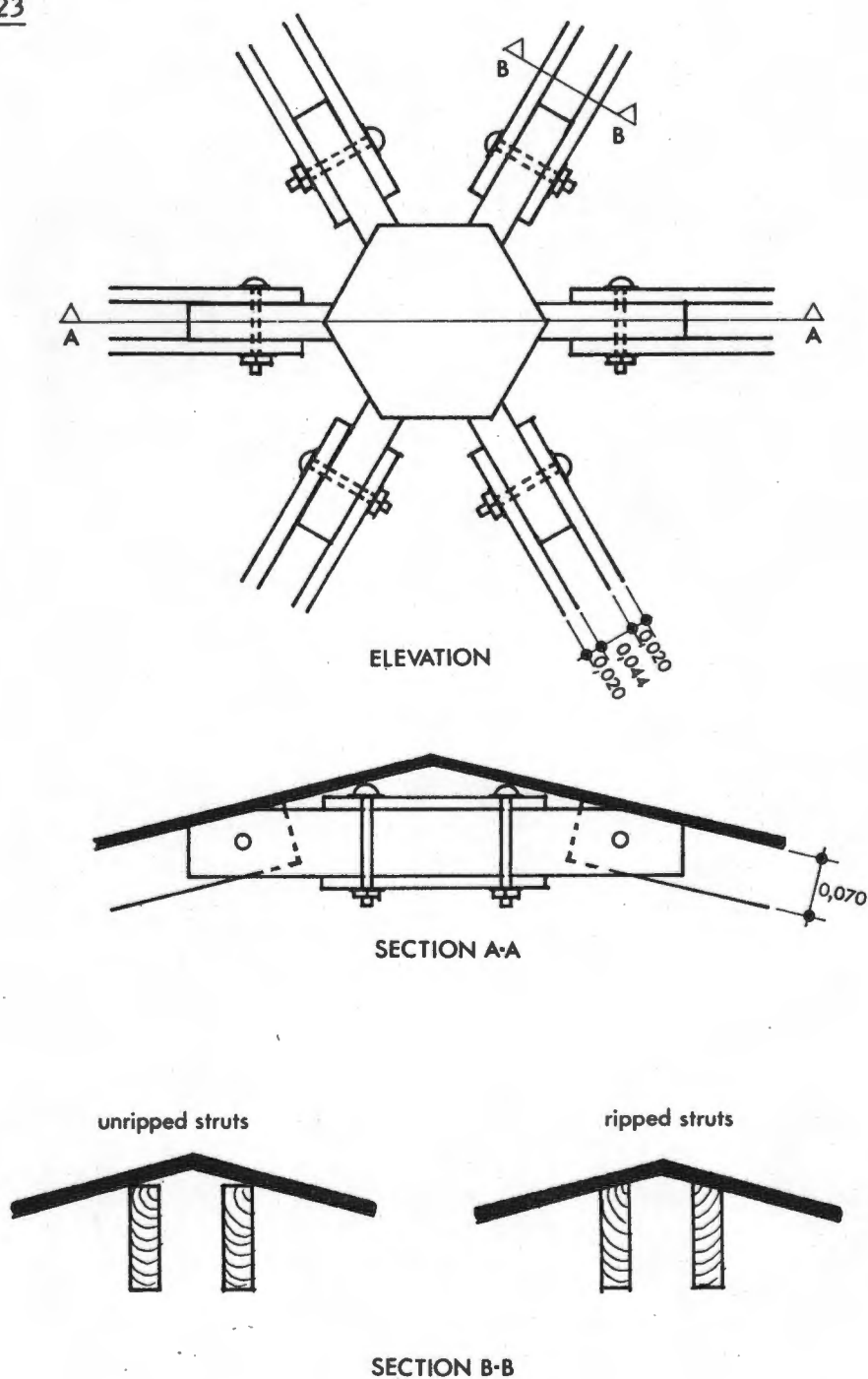


Struts and hub-arms must be cut 'over-size' to project beyond bolt-holes by a reasonable distance ( $y$ ) - approximately 50 mm.

**NOTE:** The position of 'Pivot-bolts' determines the vertexes of the dome and the correct natural alignment of struts in space.

- The second major difference between this hub system and all others, is that instead of using one 44x70 mm strut per edge, two 20x70 mm struts are used with a 44 mm gap between the 'pair' of struts - this gap is induced by the hub-arms onto which strut-ends are bolted.

Figure 4.23

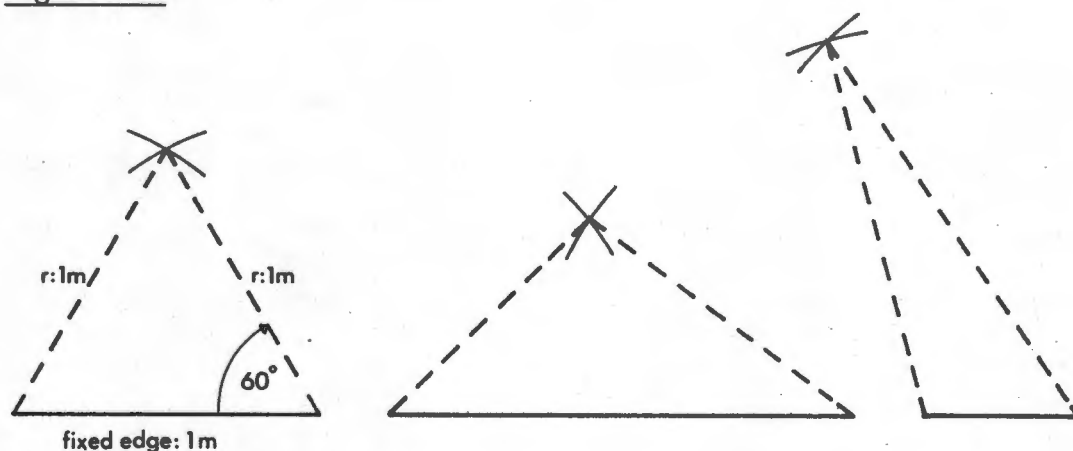


#### 4.2.1.3 Skinning and Sealing Strut-and-Skin Domes

Various sheet materials can be used to skin the dome framework. All the flat panel facets are triangular with edges of adjacent panels meeting in the centre of a strut. Thus panels have a bearing width of 22 mm along the length of each edge.

Panels must be accurately cut to size with edge-lengths corresponding with the respective strut lengths - accurate edge-lengths will automatically produce the required face angles. Assume a triangle to have three equal edge-lengths of 1 m. To set-out the triangle, one edge is fixed; arcs are drawn 1 m from each end of the fixed edge - their point of intersection defines the unknown vertex of the triangle. All face angles will inherently be  $60^\circ$ . Any triangle with three known edge lengths can be similarly set-out, to automatically produce the correct face angles.

Figure 4.24



However, since all face angles are usually known anyway, a template can be set-up to check the accuracy achieved in setting-out. It is not recommended that angles are used to set-out triangles, because setting up accurate angles is much more difficult than measuring accurate lengths.

In order to minimise on waste of the standard size sheet material, a scaled drawing of panels should be used to plot cutting edges - scaled paper triangles are cut out and moved around until the most economical arrangement is found (see 5.4.1.1).

Panels are fixed to the struts by nailing, screwing or stapling, depending on the sheet material used. Accuracy in fixing panels is important so that the 22 mm bearing width is maintained all around the edges, otherwise some nails or screws might miss the strut completely. Also, if panels are fixed inaccurately, some will have to be custom-fitted, an unwarranted and laborious operation.

Sheet cladding materials to be considered in the context of this study are:

- Plywood
- Fibre-reinforced cement (FRC)
- Sheet metal

#### 4.2.1.3.1 Plywood

Since the geodesic dome has its commercial origin in the United States of America, where timber is plentiful and of good quality, many domes are sheated with 9 mm, 12 mm or 15 mm thick plywood panels. Plywood is manufactured in standard panel sizes, maximum size 1,220x2,440 m; thus scaled paper triangles should be used to find the most economical arrangement of cutting panels. Having cut triangular panels to size, they are accurately placed onto the framework, with panel-edges in alignment with the centre-line of respective struts. Panels are fixed with galvanised clout-headed nails (or staples) at 150 mm centres along edges, not less than 10 mm - and not more than 15 mm - from the panel-edge.

Untreated exterior grade plywood will not endure the sun and rain for long without delaminating. Even marine grade plywood, which is extremely expensive, requires at least two coats of acrylic paint to protect the face veneer. Along the cut edges of panels all plies are exposed in section - treatment is thus necessary to prevent delamination at edges. Along the seams, where panel edges meet over struts, special waterproofing treatment is required, especially at the vertexes.

NOTE: The Dome is a complete ROOF. Rainwater thus runs over the entire surface of the structure.

One way of sealing the dome is by applying a monolythic layer, such as fibreglass or gunite concrete over the entire dome surface, thus creating a rigid structure. Waterproofing a plywood dome in such a way that it remains slightly flexible at the joints is only effectively done by one of the following methods:

- Shingling with wood or composition shingles, such as mastic asphalt shingles.
- Fibreglassing panels individually, caulking joints, taping or bandaging over seams, and painting the entire dome with an acrylic paint.
- Covering the completed plywood dome with a layer of 'Bidim' U-14 geofabric, applied with an acrylic paint (or rubberised bitumen) and subsequently painting the entire dome with two coats of the same acrylic paint (or with a bituminous aluminium paint).
- Shingling

Wood shingles or shakes are extremely scarce in South Africa due to the lack of suitable local timber, due to the inherent fire risk and due to the



fact that without regular maintenance they have a relatively short life span. From a practical point of view they are not recommended for covering domes, because they are not malleable enough to bend over seams between panels, thus creating waterproofing problems, especially at the vertexes. In order to ensure watertightness, joints between panels should be caulked with a silicone or polysulphide sealer, or a 'Bidim' geofabric bandage should be applied along seams with rubberised bitumen before the shingles are fixed.

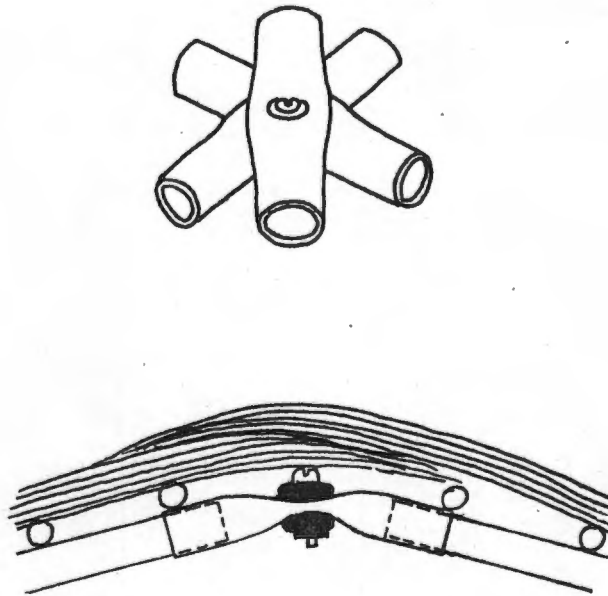
The fixing of shingles is a relatively skilled operation. They must always be three layers thick at any point - the amount of 'exposure' should thus never exceed  $\frac{1}{3}$  the length of a shingle. As the pitch decreases, the exposure is reduced. Below a pitch of  $15^\circ$ , special precautions must be taken to prevent the wind from blowing off shingles and driving water underneath. Domes with a 'vertex-zenith' orientation only have five triangles, which make up the zenith pentagon, which are at a lower pitch than  $15^\circ$ . However this pentagon is utilised as a ventilation hood anyway - being either an 'umbrella' vent or a 'cupola' vent, the pitch of the hood can be increased as required.

Wood shingles are aesthetically more pleasing than any other form of dome cladding - however in South Africa they can only be considered as a feasible alternative for very exclusive housing.

Some Alternative Ideas: In order to eliminate seams and vertexes (and concomitant waterproofing problems), the triangular-faceted dome framework may have horizontal circular hoops of flexible reed saplings attached at approximately 250 mm centres, to which the shingles are fixed. No plywood sheathing is necessary, but a plastic damp-proofing membrane is placed between the timber dome framework and the circular hoop battens.

Shingles, being linear or flat, are however not suitable to cover spherical surfaces with - at the top of the dome the circle tightens sharply, thus necessitating the cutting of shingles into wedge-shapes. Alternatively the dome may be thatched, which is the most efficient method of sealing a spherical structure and one which has a strong traditional flavour in the South Africa context. In addition, wattle or Port Jackson willow saplings may be used as struts, since a the geodesic framework consists of short lengths and suitable straight lengths of saplings are abundant. The hub-connections for a sapling framework (as for most frameworks made of circular struts) consist of flexible rubber or plastic piping (or metal tubing), joined as illustrated below.

Figure 4.25



Mastic Asphalt Shingles: Sealing domes with asphalt shingles is a popular and efficient method of waterproofing the structure. Besides being used on new houses, many existing domes which developed leakage problems have been successfully waterproofed with asphalt shingles. Fuller's own home in Carbondale, Illinois, falls within this category.

The major advantage of asphalt shingles is their flexibility. They can thus be lapped and laced over joints between cladding panels. Domes which are frequency-modulated into three or more subdivisions never have panels meeting at an external angle or 'breaking angle' greater than  $195^\circ$ . Thus shingles are bent through a maximum angle of  $15^\circ$ , which is easily accomplished. As the frequency of subdivision increases the dome becomes more spherical and angles between panels become smaller. Asphalt shingles are fixed to 9 mm, 12 mm or 15 mm plywood sheathing by nailing or stapling. Heat welding of edges is only necessary at pitches less than  $12^\circ$  or greater than  $60^\circ$ .

An asphalt tile called 'Vertile' is available in South Africa; another called 'Sopratuile 100' was recently introduced to the South African market. Both products have been extensively tested and used in the United States and in France. The tiles are glass-fibre reinforced and protected by crushed mineral granules which are set in a ceramic coating.

- Fibreglassing, Caulking, Bandaging and Painting

Another method of sealing plywood domes is to apply a layer of fibreglass onto panels with resin before assembly. Once panels are fixed to the framework, joints between panels are caulked with a mixture of resin and thickening powder; then a 100 mm wide fibreglass bandage is applied over the seams. Finally the entire dome surface is painted either with a final

coat of resin and white pigment or with an acrylic paint. The fibreglass bandage inherently creates a rigid joint between panels - the resin caulking requires this rigid bond, as any movement between panels would cause cracking. Alternatively, joints may be caulked with a resilient mastic and sealed with a 100 mm wide 'Bidim' U-14 bandage, which is applied over the seam and impregnated either with an acrylic paint or with rubberised bitumen, resulting in a joint which allows for slight movement between adjacent panels. At the vertexes the bandage overlaps to form a three-layer thick protection over the most critical points of waterproofing.

The application of self-adhesive tapes over seams is not recommended because, over time, the bond will inevitably loosen at some points. Pressure sensitive tape, such as 'Ditsit', will only adhere to certain surfaces - it will not stick to itself at the vertexes where it overlaps, because the tape is coated with a release agent or with a layer of aluminium foil so that it peels off the roll easily.

- 'Bidim' U-14 and Acrylic Paint or 'Bidim' U-14, Rubberised Bitumen and Bituminous Aluminium Paint

Probably the most economical and efficient way of sealing a plywood dome is by covering the entire dome surface with a layer of 'Bidim' U-14 polyester geofabric which is applied and simultaneously impregnated with an acrylic paint. Another two coats of acrylic paint completes the sealing process. The initial impregnating coat has a much lower coverage than the subsequent two coats, as the geofabric absorbs the paint rapidly.

Acrylic paints have recently become the subject of much scientific research and development. Being basically emulsion paints, pure acrylics are not totally impervious and require a sufficient proportion of resin and

latex in order to serve as an effective waterproofing compound. There are many acrylic paint systems on the market, such as 'Klodek', 'Nuseal' and 'Weatherguard'.

Waterproofing acrylic compounds are relatively expensive. There are a number of bituminous paint systems on the market which are more economical and which provide a perfectly adequate impervious seal, but are prone to rapid ultra-violet degradation. Thus rubberised bitumen is only used to impregnate and fix the geofabric; the subsequent two coats are of a bituminous aluminium paint, such as 'Synthapruf', which creates a bright reflective surface, thus protecting the bitumen from direct solar radiation.

Timber housing, as such, is accepted by the building codes and regulations in the United States of America and in most other countries around the world, because it is an efficient form of construction in terms of structural strength, economy, aesthetics, thermal comfort and, with adequate workmanship, accurate detail and proper treatment, the structure is also efficiently impervious and durable. The major problem with timber housing is the inherent fire-risk involved. It is assumed that the fire-risk in a dwelling is determined by the rate of fire spread within the structure - most fires start inside a house and spread through the ceiling to the structural framework. Thus, by using fire-rated ceiling materials and by introducing 'fire-stops' to prevent air ventilation, acceptable standards of construction should be possible.

A pertinent ecological problem is that serious deforestation is occurring all around the world. Thus unless timber can be grown at the same rate as it is used, the scale of timber housing is inevitably limited.

#### 4.2.1.3.2 Fibre-reinforced Cement

9 mm FRC 'weatherboard' unpressed flat sheet is an ideal cladding material for domes. Due to the mass repetition of similar panels, it may be possible to set up a press to cut panels to the required size while the FRC is still in a 'wet' state.

The impact resistance of the material is questionable. If necessary, the timber framework may be triangularly reinforced with additional framing struts, thus frequency-modulating each triangular facet of the dome. It should not be necessary to subdivide each facet into more than four smaller triangles, thus modulating to an edge-frequency of two subdivisions (see 5.2.1.1 and 7.2.1).

FRC panels are pre-drilled along their edges to take 3,25 mm-diameter brass screws which are used to fix panels to struts. Screws must be carefully fixed so that panel-edges do not crack. A new 'nailable weatherboard' FRC panel has recently been put on the market - this could simplify the fixing of panels dramatically, especially if industrial stapling becomes possible.

Having fixed panels to the framework, the joints between panels are waterproofed by applying a 'Bidim' U-14 bandage along seams with rubberised bitumen. The entire dome surface is then coated with an acrylic emulsion paint or with a bituminous aluminium paint. This system is certainly the cheapest method of waterproofing the dome efficiently, as the coverage of paint over the asbestos panels is very high.

If deemed necessary for the purpose of aesthetics, waterproofing or impact strength, FRC panels may be covered with a layer of 'Bidim' geofabric or with 'Vertile' asphalt tiles. This would however increase the

cost substantially. It must be noted that 'Bidim' is an extremely cheap fabric and that almost the entire cost increase is due to the additional paint required to impregnate the fabric. 'Vertile' asphalt cannot be nailed onto the panels; thus 125 mm wide 'Irex' strips are heat welded onto primed panels at 450 mm centres - then the 'Vertile' tiles are heat welded onto the 'Irex' strips. At the seams tiles are lapped and laced as before.

The fibre presently being used to reinforce the FRC sheet panels is asbestos, the use of which is becoming increasingly emotionally charged because of the related health hazards. However research is continuing to find an alternative fibre with equivalent tensile strength and long-term durability. This research is being conducted behind closed doors and one can only assume that progress is being made. It must be stressed that over the last few years the handling of raw asbestos has been subject to very stringent health regulations and that the present manifestation of asbestosis is a result of careless mining and production practices a decade or two ago. The disease lies dormant in the human body for many years and only manifests itself when the lungs are attacked by another, possibly totally unrelated, disease. Thus the success or failure of present health regulations cannot be assessed until at least a decade from now. It is widely believed that the present spate of asbestosis is only a short-term problem, unless preventative measures are unsuccessful. The extremely unique properties of asbestos are such that careful consideration must be taken before possibly unwarranted emotions result in its forced removal from the market. Another point to consider is that once an asbestos-cement product has been manufactured, there is no further danger to public health, because the asbestos is by then immersed in the hardened cement and thus cannot be released into the atmosphere, unless the asbestos-cement product is cut.



#### 4.2.1.3.3 Sheet Metal

Sheet metal panels, both aluminium and galvanised steel, have been extensively used in dome construction. However they are far better suited to being manufactured into composite stressed skin panels with flanged edges, instead of being used to skin a timber framework. They are thus discussed in the next section which deals with 'Panel' domes.

#### 4.2.2 Panel Domes

The basic difference between 'Panel' domes and 'Strut-and-Skin' domes, is that the manufactured panel of the former, serves the function of both strut and skin, providing structural strength and a covering.

It is recommended that the 'Panel' dome system be adopted as the principal method of low-cost geodesic dome construction for a number of reasons:

- Ease of Assembly: The on-site assembly procedure is simplified to the utmost, entailing basically the bolting together of colour-coded panels in the correct sequence and then sealing the joints between panels, waterproofing and painting the structure. The major proportion of skilled and time-consuming work is executed during the process of manufacture in a controlled factory environment. Thus the 'Panel' dome could easily be manufactured into 'Kit' form and be assembled on site on a 'self-help' basis.
- Speed of Assembly: The on-site assembly-time is minimised. The duration from the completion of the foundations to the completion of the entire dome should not exceed one week, depending on the number of helping hands available and on the productivity achieved (see 7.3). Unless panels are carefully assembled according to the

colour-coding and sequence described in the instruction manual, mistakes and subsequent time-consuming corrections are inevitable. Supervision is essential!

- Economy: There is a definite cost-saving over 'strut-and-skin' construction, because no hub-connections are required and because the mass-production of manufactured components inherently leads to cost-savings as marginal costs decrease due to economies of scale.

There are three basic methods of manufacturing panels:

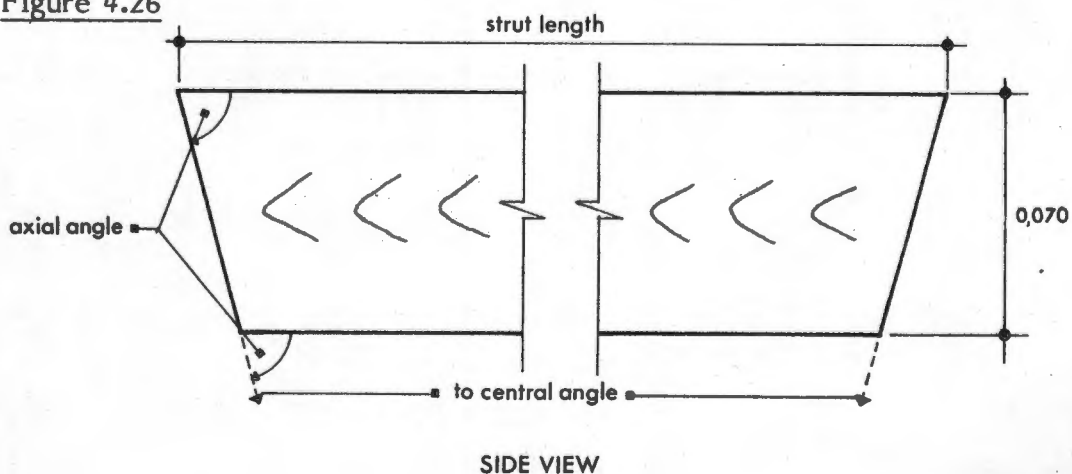
- Sheet panels on timber frames
- Sheet panels with flanged edges
- Moulded panels.

#### 4.2.2.1 Timber-framed Panels

The framing timber is ex 25x75 mm S.A. Pine - being planed all round the effective cross-sectional area is 20x70 mm. The length of each strut is calculated as before, by the product of the dome radius and the relevant chord factor. Hub-connections are not necessary - thus strut lengths are not shortened as previously. Each strut is angle-cut as follows:

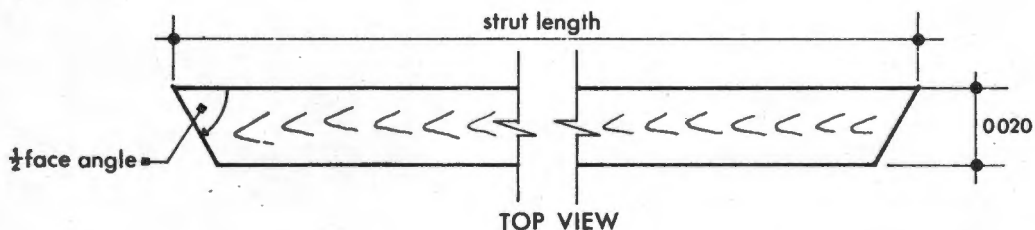
- Splay-cut (once at each end):  $90^\circ$  minus Axial Angle

Figure 4.26



- Mitre-cut (once at each end):  $90^\circ$  minus  $\frac{1}{2}$  Face Angle

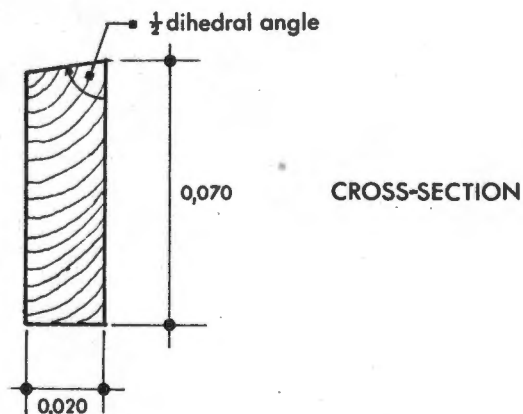
Figure 4.27



NOTE: As before, splay- and mitre-cuts may be compounded - thus, with a suitable jig, only one cut is necessary.

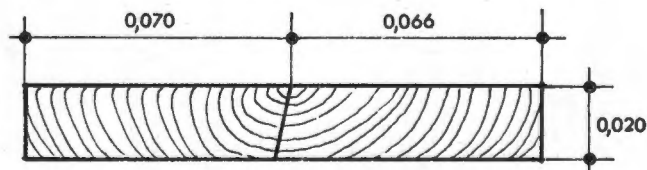
- Bevel-cut (once along top edge):  $\frac{1}{2}$  ( $180^\circ$  minus Dihedral Angle)

Figure 4.28



To save on 'ripping' time, a 20x136 mm timber may be cut in half as follows:

Figure 4.29



This cuts ripping time by half - being an extremely time-consuming operation, the savings achieved could be substantial.

Once struts have been cut to length and angle-cut, they are stacked in respective colour-coded piles. Then each strut is drilled accurately at three (or four) points along its length so as to ensure perfect alignment of bolt-holes when panels are bolted together on site. Plywood or FRC flat sheet panels, cut to the required triangular shape, are nailed or screwed respectively to the frame. Fixing points should not be further apart than 150 mm for nails and 350 mm for screws and not closer than 10 mm - or further than 15 mm - from the edge of panels.

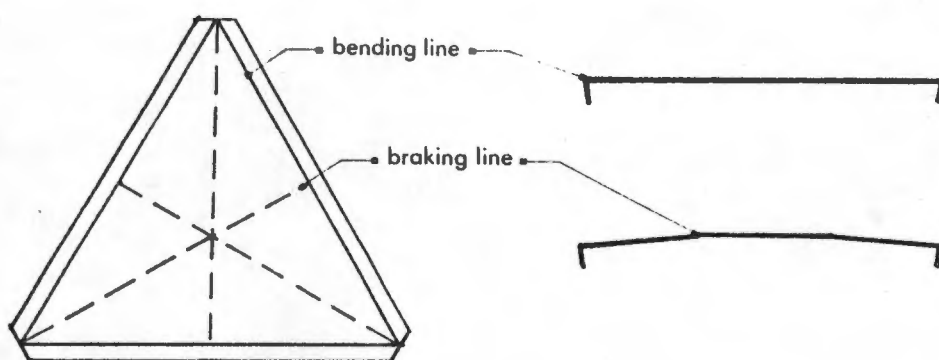
NOTE: Dome A is a 'Panel' dome - for more construction details refer to Chapter 5.

On site, the completed panels are bolted together with 8 mm-diameter, 50 mm long galvanised bolts along each edge, by aligning the pre-drilled holes in struts. Joints between panels are sealed as described previously (see 4.2.1.3 and 5.4.3). However, in order to get an improved seal, a 50 mm wide neoprene strip or a bitumen-impregnated 'Bidim' strip may be placed between panels before they are bolted together. Alternatively the strips could be fixed onto panel edges during the process of manufacture.

#### 4.2.2.2 Flanged Panels

This system of dome construction does not employ any timber struts, unless deemed necessary for strength. The most common material used is sheet metal, either galvanised steel or aluminium, which is bent along the edges of the triangular sheet to form a flanged framework around the panel. For additional strength, the flat sheet is cross-braked along a line from each vertex of the triangle to the centre of the opposite side.

Figure 4.30



There are two easy methods of joining completed panels on site:

- Bolting
- Inverted standing seam, riveted.

Figure 4.31



NOTE: Fixing points should be as close as possible to the skin and vertexes - this strengthens the dome considerably.

The inverted standing seam results in a stronger structure. The additional return flanges must be carefully considered when cutting panels - half of the panels making up the complete dome have return flanges along two edges, whereas the others only have one return flange - this is of the utmost importance in designing the optimal interlocking system. However, the additional design problems and the difficulty in bending return flanges in conventional bending brakes, makes this method of dome construction economically unviable, especially for low-cost housing.

Figure 4.32

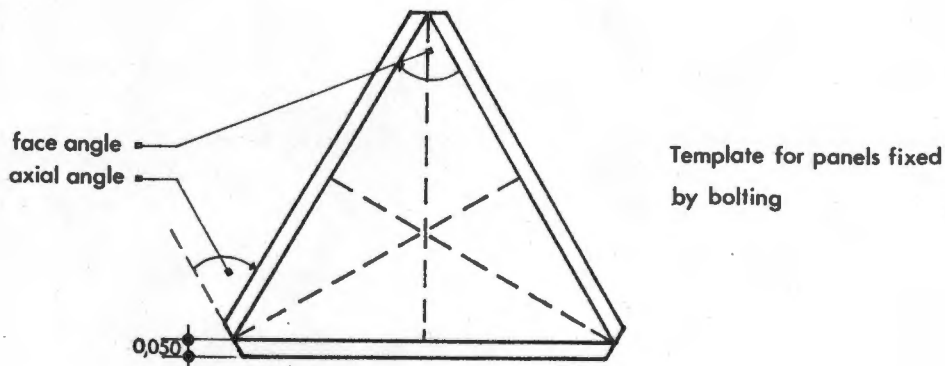
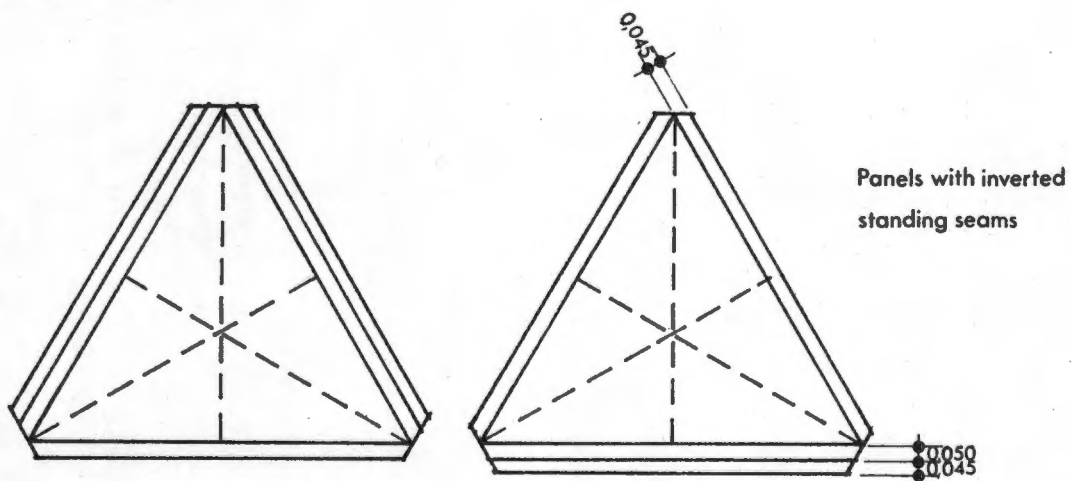


Figure 4.33



The temper or hardness of sheet aluminium determines the degree of malleability - if the aluminium is too hard it will crack or fissure when bent. However soft temper or half-hard temper aluminium may need to be reinforced along seams with timber struts. In effect the dome is then a timber-framed panel dome. The frame is manufactured as before (see 4.2.2.1). The sheet aluminium is placed onto the framework, dressed over timber struts at the panel-edges and stapled (or nailed) to the side of the frames.

Panels are assembled and fixed as in other timber-framed panel domes - with 8 mm-diameter galvanised bolts. A 50 mm wide neoprene strip may be sandwiched between adjacent panel-edges as before. Joints between panels are caulked with a silicone or polysulphide sealer. Alternatively joints may be sealed by applying a 'Bidim' bandage along seams as before - however unless the dome is subsequently painted, the bandage is aesthetically unpleasing.

#### 4.2.2.3 Moulded Panels

Various materials may be moulded into the form of panels with composite flanged edges while they are in a 'wet' state. The basic structure of the panels consists of a high-tensile strength fibre combined with a chemical compound which binds the fibres and provides rigidity and compressive strength. The most commonly used fibres are glass, asbestos and metal, while the most common binding agents are resin and cement. In combination they form the four most common compound materials used in the manufacture of moulded panels.

- Fibreglass-reinforced resin-bound panels
- Asbestos-reinforced cement panels
- Steel-reinforced cement panels
- Glass-reinforced cement panels.

A suggested alternative fibre is wood. Although wood-fibres have been used in the manufacture of acoustic ceiling panels, their application in serving as structural fibres in densely-bound external cladding elements has thus far been almost unheard of. However a vast quantity of unwanted 'weeds', such as the Port Jackson willow, could feasibly be 'rolled' into fibres of considerable tensile strength and used to reinforce cement panels.



However the use of moulded panels in dome-construction is unusual because of inherent production problems. Firstly, the flanges are bent through an angle slightly greater than  $90^\circ$  resulting in edges which are vulnerable to cracking along bending lines and creating difficulty in demoulding panels, unless moulds have at least one hinged edge.

Another production problem is that, although only a few standard moulds are required, the frequent repetition of similar panels necessitates a number of similar moulds to allow for sufficient output. Because of the curing time involved, each mould is occupied for a relatively long period of time - for the duration of initial setting and hardening. Moulds are expensive to manufacture and their re-use value must be accurately ascertained in determining the cost of moulded panels. The re-use value of a mould is determined by the number of times the mould can be re-used and by the frequency cycle of re-use, which depends on the required initial curing period of a particular system.

## CHAPTER FIVE

### 5. THE DESIGN AND CONSTRUCTION OF PROTOTYPE, DOME A

#### 5.1 Introduction

##### 5.1 'Everite dome, Brackenfell



The prototype was first partially erected in October 1983 at the Everite factory in Brackenfell, Cape Town. In response to a newspaper article, the owner of the World of Birds in Hout Bay requested the dome to be transferred there and completed as an office. Working drawings (see 5.2) were submitted to the Divisional Council of Cape Town, who, with the consent of the Hout Bay Ratepayers Association, approved the plans (for



office purposes only!). Various design details were altered from the original structure, notably the foundations. Although the analysis which follows describes the construction of the re-erected dome, some reference is made to the original structure to emphasise pertinent design improvements.

The dismantling of the original dome was a very simple task, an inherent feature of lightweight 'kit-form' panel construction. It took two people approximately four hours to dismantle the 'Standard Shell' of Dome A. The panels were transported by means of a Volkswagen kombi which, by weight, could easily transport the 72 panels making up the 'Standard Shell' in one load; however, by volume, two trips were necessary.

Most of the materials for construction were sponsored by various suppliers, notably Federated Timbers and Everite - other sponsors were Cape Bolt and Nut, Corobrik, Gundle Plastics, Noel Hunt Geofabrics, P.G. Glass, Ready Mixed Concrete, Vadek Paints and Vialit.

## 5.2 'World of Birds' dome, Hout Bay



## 5.2 Vital Statistics and Working Drawings of Prototype Dome A

|                                  |   |
|----------------------------------|---|
| ⊗ <u>Geometry:</u>               | 3-frequency, 5/8-sphere, icoso-alternate breakdown, vertex zenith   |
| <u>Diameter</u> . . . of sphere: | 6,800 m   |
| . . . of floor:                  | 6,680 m   |
| <u>Floor Area:</u>               | 35 m <sup>2</sup>   |
| <u>Height at Apex:</u>           | 4,000 m   |
| <u>Type of Structure:</u>        | 'Panel' dome - complete shell, with four standard windows, one standard door, a ventilation flue/hood and a paved floor; no ceiling, no electricity, no plumbing, no internal partitions. |
| <u>Approximate Total Cost:</u>   | R6 000 (see 7.3)  |

⊗ The decision to use a 3μ, 5/8-sphere, icoso-alternate design was made during the very early stages of research - while building scaled models. The geometry of geodesics can hardly be understood without recourse to 3-dimensional scaled models. Pertinent factors favouring the 3μ alternate design are mentioned on pages 156 and 157. In addition to these, the following practical considerations are significant:

- What floor area should the dome enclose?

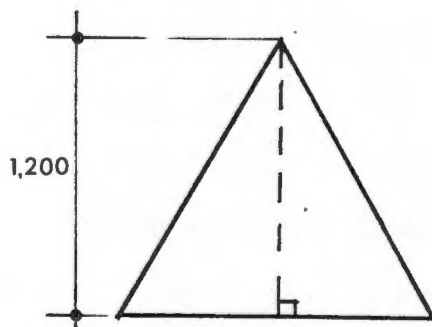
The minimum floor area of a core-house is widely accepted to be 27m<sup>2</sup>. At Khayelitscha this minimum is applied, based on wide research of British and French standards as regards low-income core shelter in Third World countries.

On the other end of the scale there is the once standard sub-economic NE 51/9 house with a floor area of  $54\text{m}^2$ . Under present economic conditions, the NE 51/9 house is no longer affordable to low-income families, whereas the core houses of Khayelitscha seem to be in great demand (at R 7000).

The dome (DOME A) is not a core as such, but a complete building envelope, large enough not to require immediate extensions as a core house does. The addition of one room ( $8\text{m}^2$ ) to a core house is assumed to be essential to adequately house a family of six persons. Thus a floor area of  $35\text{m}^2$  is the minimum requirement.

- The next parameter of significance is that a maximum standard size rectangular cladding panel has one limiting dimension of 1,200m. In order to minimise on wastage, each triangular panel should measure 1,200m from one vertex perpendicularly to the opposite side (see p147).

By calculation it is found that a 3μ alternate design, satisfying the above parameter, results in a dome with a floor area of  $35\text{m}^2$ .



- The 5/8 sphere cut-off plane is preferred to a hemispheric truncation, because the curvature of the dome only starts 1,2m above floor level. Thus the floor space is utilised optimally, whereas a hemispheric dome has insufficient headroom around the internal perimeter.
- The 3μ alternate design allows for relatively simple nesting by fusion (see 7.2.3).

NOTE: See Chapter 6 for 'Alternative Geodesic Designs'

## NOTES ON WORKING DRAWINGS

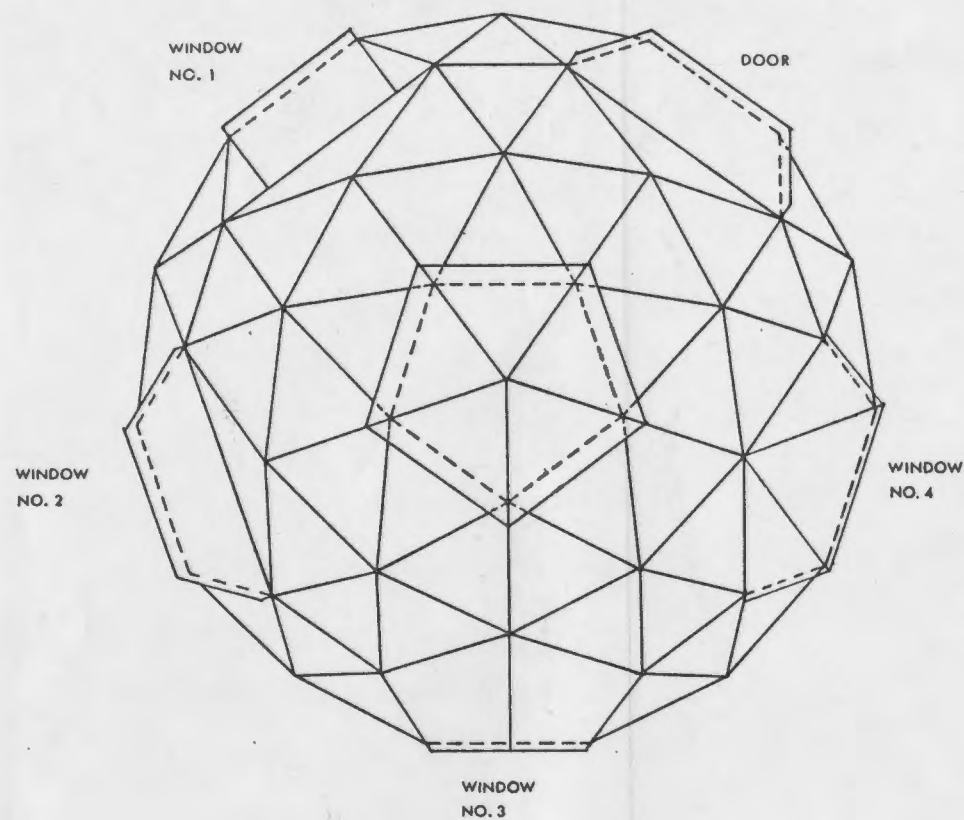
- (1) The original drawings were set-out on A2 size paper. A 65 per cent reduction to A3 results in all scales (as given) changing as follows:

| <u>Scale given</u> | <u>Actual scale (approximate)</u> |
|--------------------|-----------------------------------|
| Full size          | 1:1,5                             |
| 1:5                | 1:7,7                             |
| 1:10               | 1:15,4                            |
| 1:20               | 1:30,8                            |
| 1:50               | 1:77,0                            |

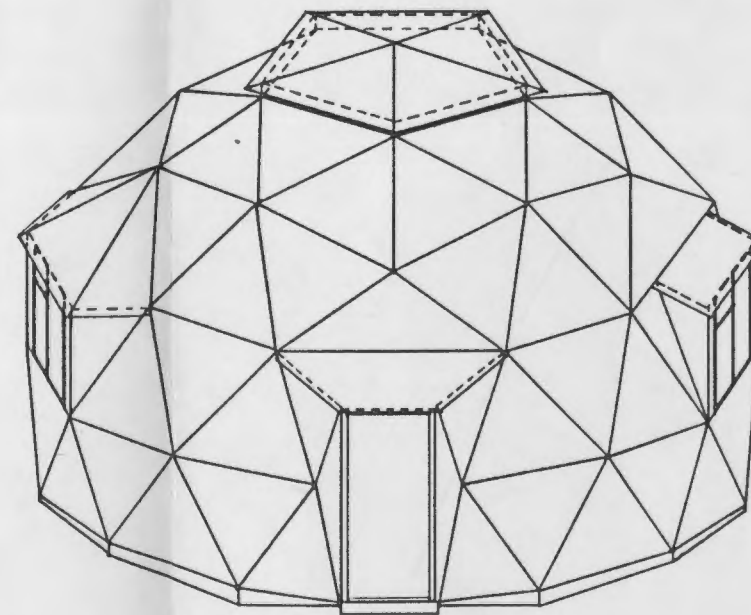
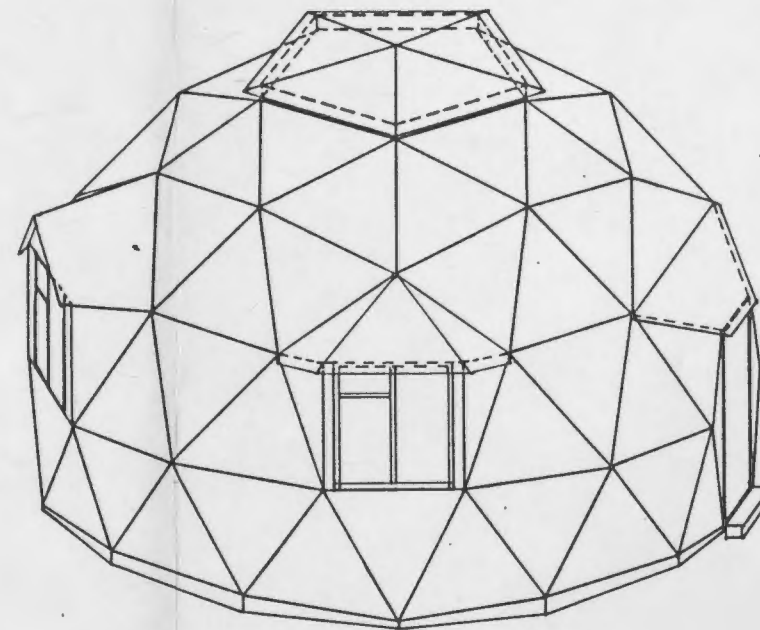
- (2) The position of respective window-sets varies between the drawings and the photographs. In addition, window-set No. 2 (basically a combination of window-sets Nos. 1 and 3) is not shown in the illustrations, as it was replaced by a custom-fitted picture window (see Illustrations 5.23, 5.24, 5.32 and 5.34).
- (3) The numbering of panels in the illustrations does not correspond with Working Drawing No. 6. The reason for this is that, once the original dome had been dismantled, all FRC panels were removed from their timber framework; then all frames were painted with creosote and the inside surface of panels was painted with white acrylic paint. Panels were subsequently fixed back onto the frames. Since all panels are identical they were randomly fixed to the frames, which were in turn randomly erected on site. Thus the original numbering became redundant.
- (4) Working Drawing No. 2 is only a suggested floor plan - the prototype, as it stands now, has no partitions.

(See 7.2.1. for alternative methods of internal space subdivision)





TOP VIEW



SIDE VIEWS

## DOME A VITAL STATISTICS

GEOMETRY: 3-frequency geodesic,  $\frac{5}{8}$  sphere,  
icosa-alternate breakdown,  
vertex zenith

DIAMETER: ... of sphere: 6.800m  
... of floor: 6.680m

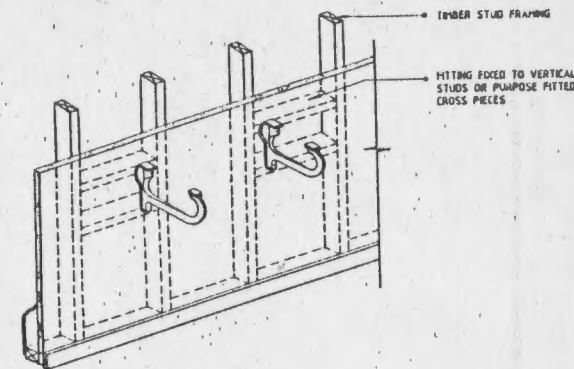
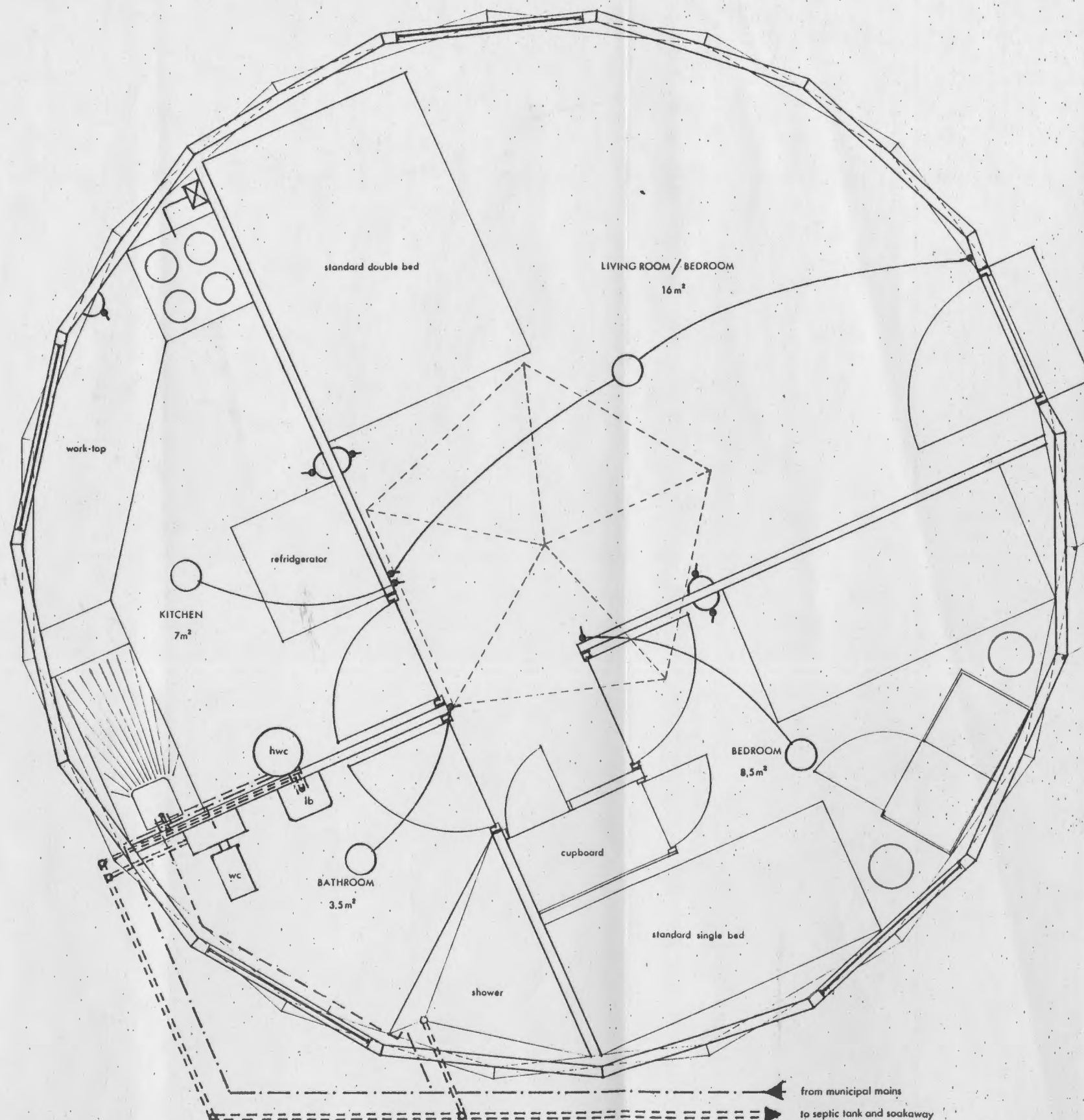
FLOOR AREA: 35m<sup>2</sup>

HEIGHT AT APEX: 4.000m

CONSTRUCTION: PANEL DOME  
72 identical 'standard' panels  
4 windows  
1 door  
1 vent hood

DOME A  
drawing no. 1  
PERSPECTIVE VIEWS  
approximate scale 1:50  
drawn by: p.waizenegger  
date: may 1984





SKETCH SHOWING DETAIL FOR WALL MOUNTED WASH HAND BASIN

SECTION AT FLOOR LEVEL

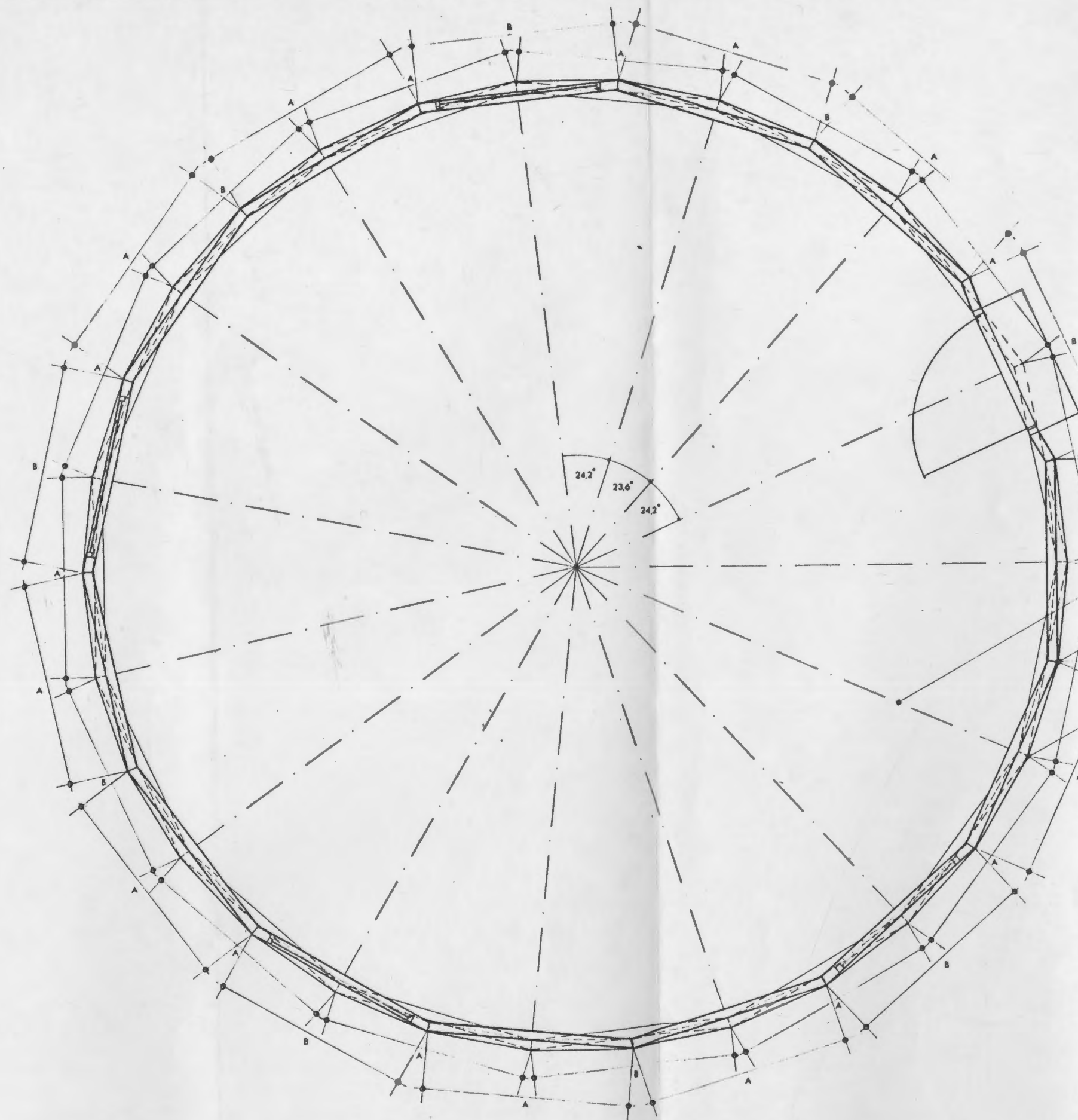
SECTION AT WINDOW-SILL LEVEL: 1.180m above FFL

### plumbing & drainage

- cold water supply
- hot water supply
- == drainage
- ⊕ rodding point

**DOME A**  
drawing no. 2  
**FLOOR PLAN**  
scale 1:20

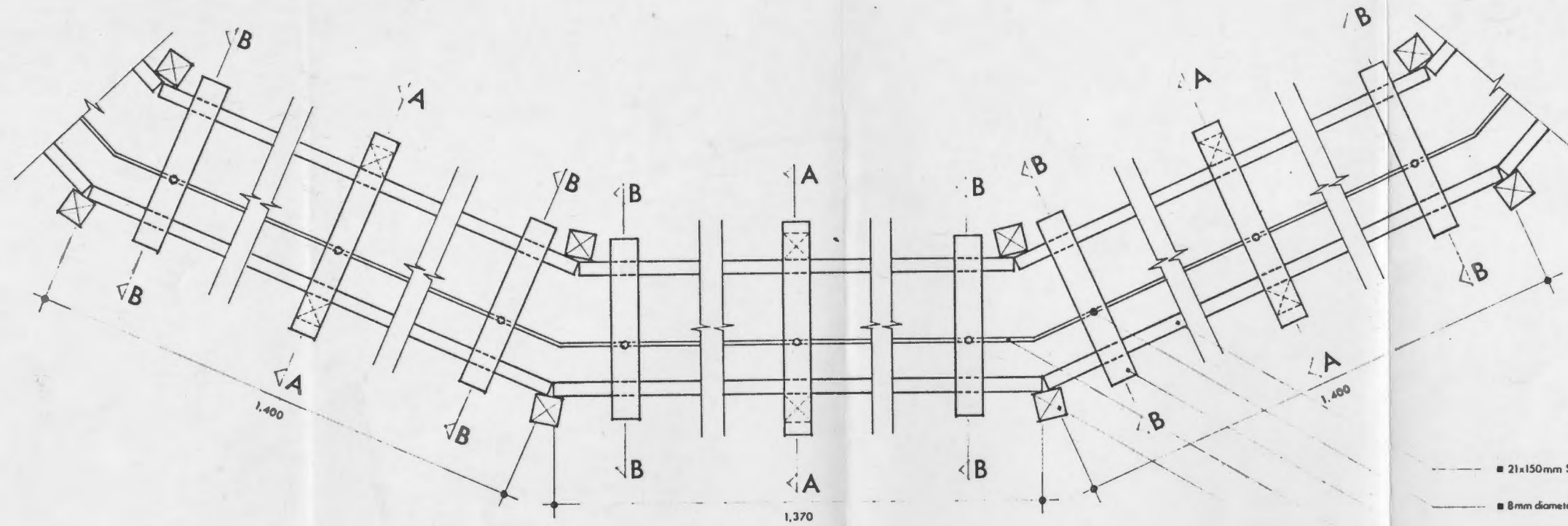
drawn by: p.waizenegger  
date: may 1984



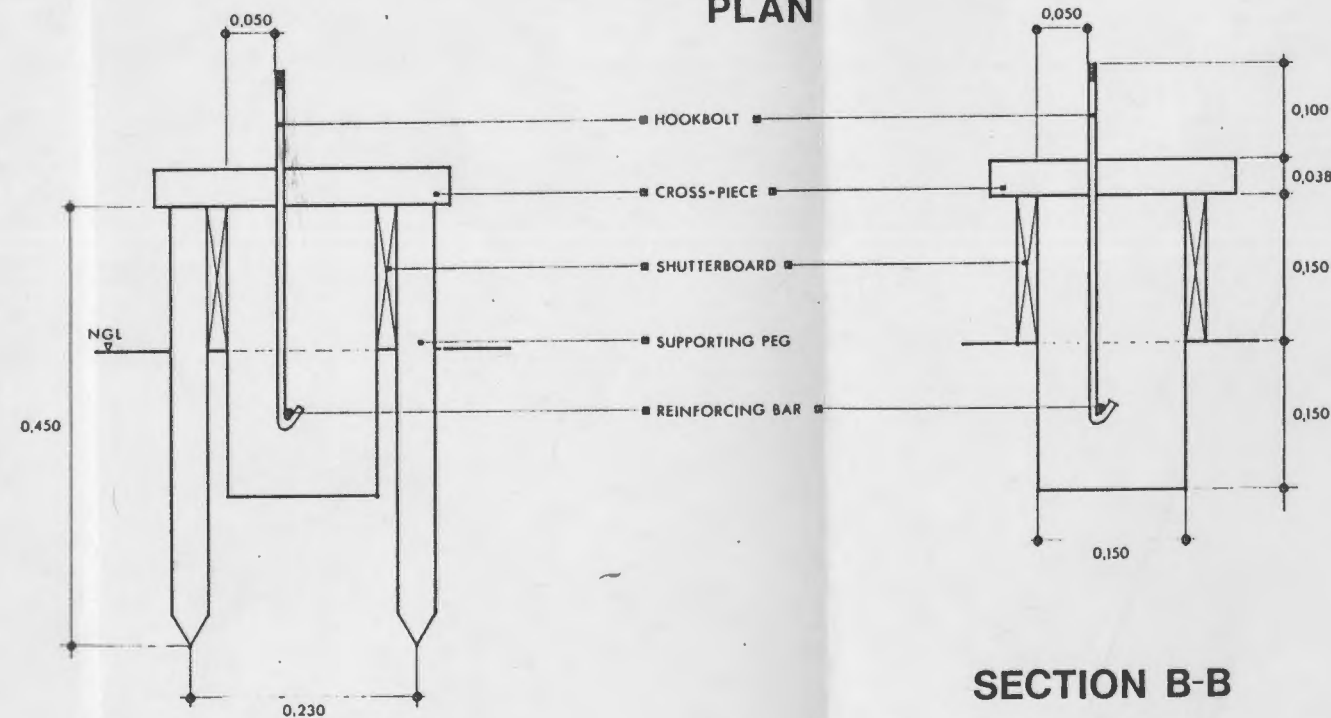
NOTE: A = 1,400m  
B = 1,370m

- DIMENSIONS AT FLOOR LEVEL
- DIMENSIONS AT WINDOW-SILL LEVEL: 1180m above FFL
- SETTING-OUT LINES: R=3,340m
- UPRIGHT BASE PANEL - WITH VERTEX POINTING UP
- INVERTED BASE PANEL - WITH VERTEX POINTING DOWN

**DOME A**  
drawing no.3  
**SETTING OUT**  
scale 1:20  
drawn by: p.waizenegger  
date: may 1984



PLAN



SECTION A-A

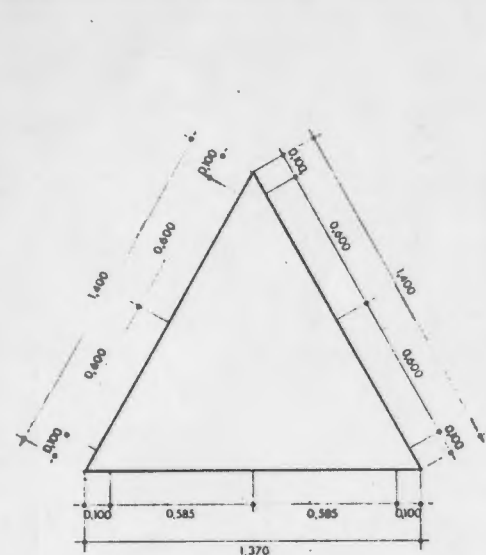
SECTION B-B

- 21x150mm SHUTTERBOARD
- 8mm diameter, 350 mm long HOOK BOLT
- 38 x 38 mm sawn SA pine CROSS-PIECE with 8 mm diameter hole to take hookbolt
- 8mm diameter (Y8) STEEL REINFORCING BAR fixed to hookbolts
- 38 x 38 mm sawn SA pine SETTING-OUT PEG

NOTE:

- FOR UNREINFORCED UPRIGHT BASE PANELS:  
THREE CROSS-PIECES PER SHUTTER (as shown above)
- FOR REINFORCED UPRIGHT BASE PANELS:  
FOUR CROSS-PIECES PER SHUTTER (see drawing no. 5)

**DOME A**  
drawing no. 4  
**FOUNDATIONS:**  
**FORMWORK DETAILS**  
scale 1:5  
drawn by: p.waizenegger  
date: may 1984



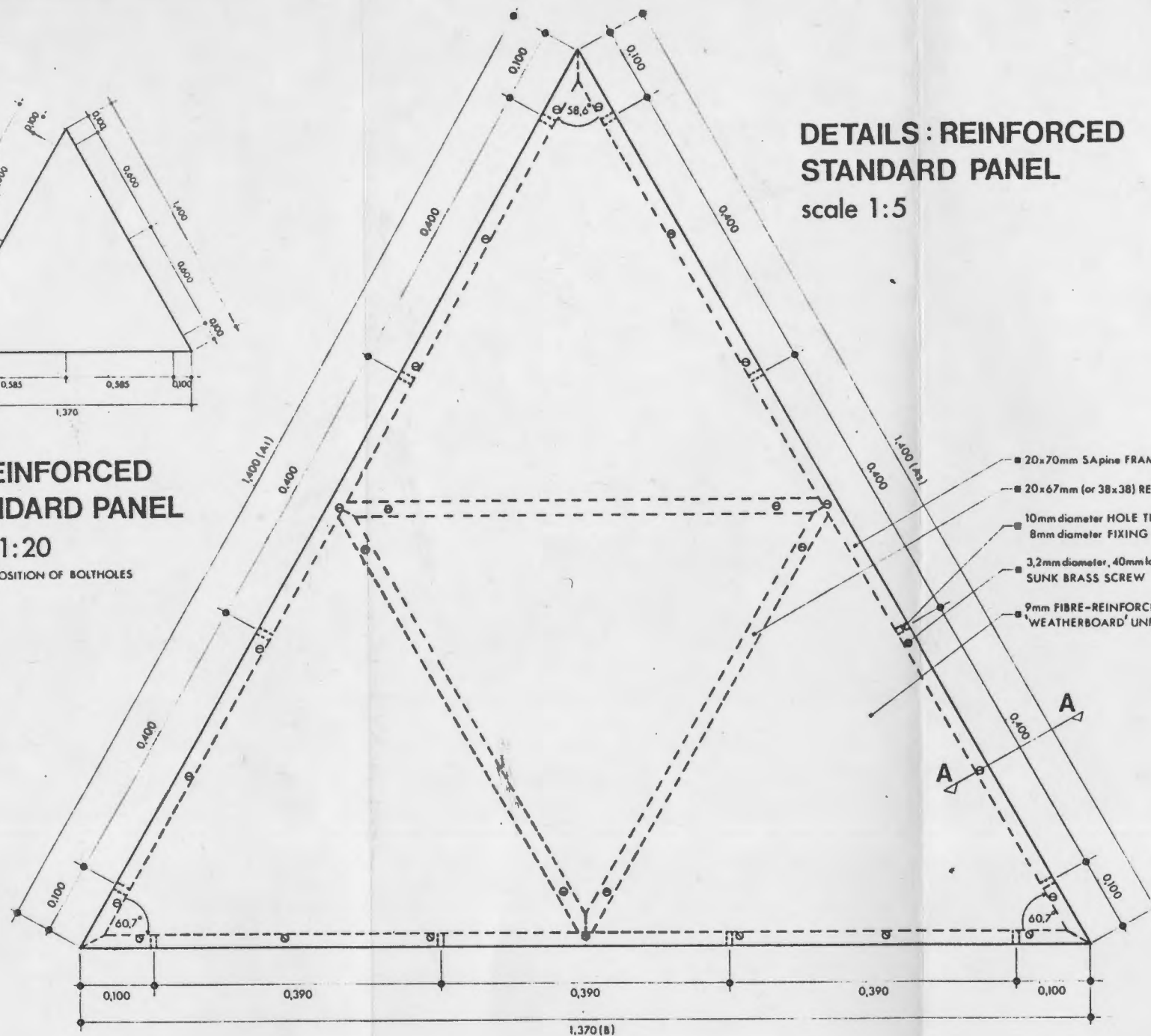
### UNREINFORCED STANDARD PANEL

scale 1:20

SHOWING POSITION OF BOLT HOLES

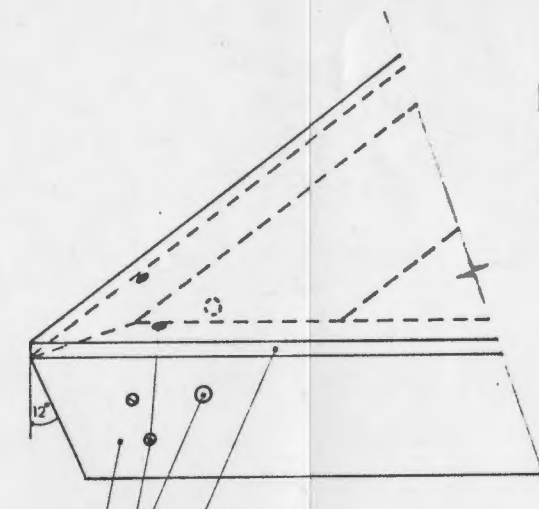
### DETAILS: REINFORCED STANDARD PANEL

scale 1:5



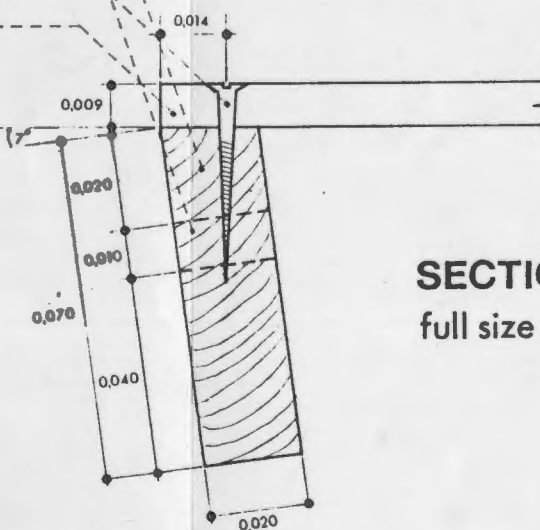
### PERSPECTIVE VIEW OF PANEL VERTEX

not to scale



### SECTION A-A

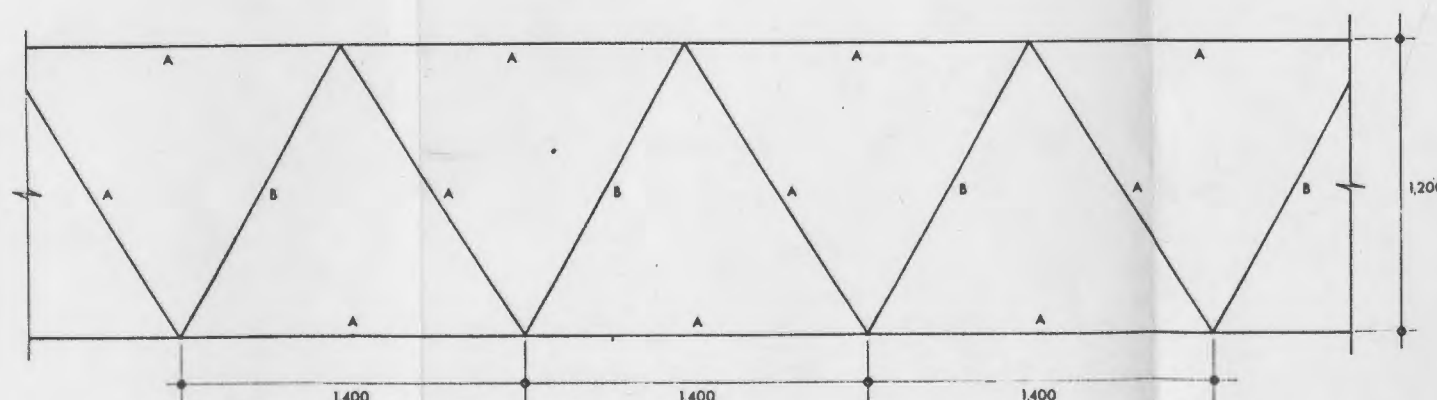
full size



### CUTTING PATTERN

scale 1:20

SHOWING MOST ECONOMICAL CUTTING PATTERN  
OF STANDARD 1,200m WIDE FRC FLAT SHEET  
CLADDING



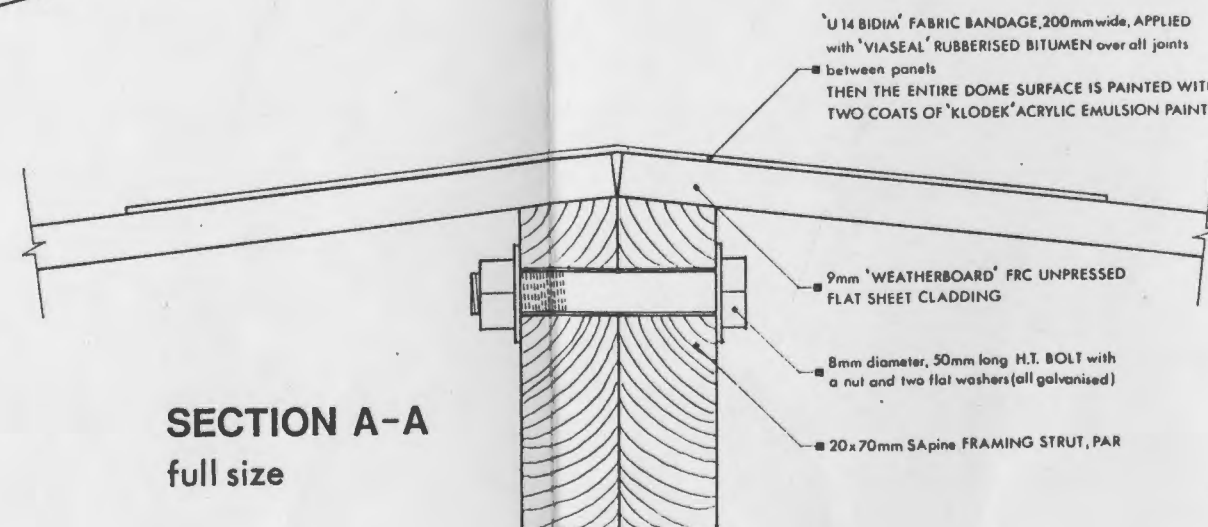
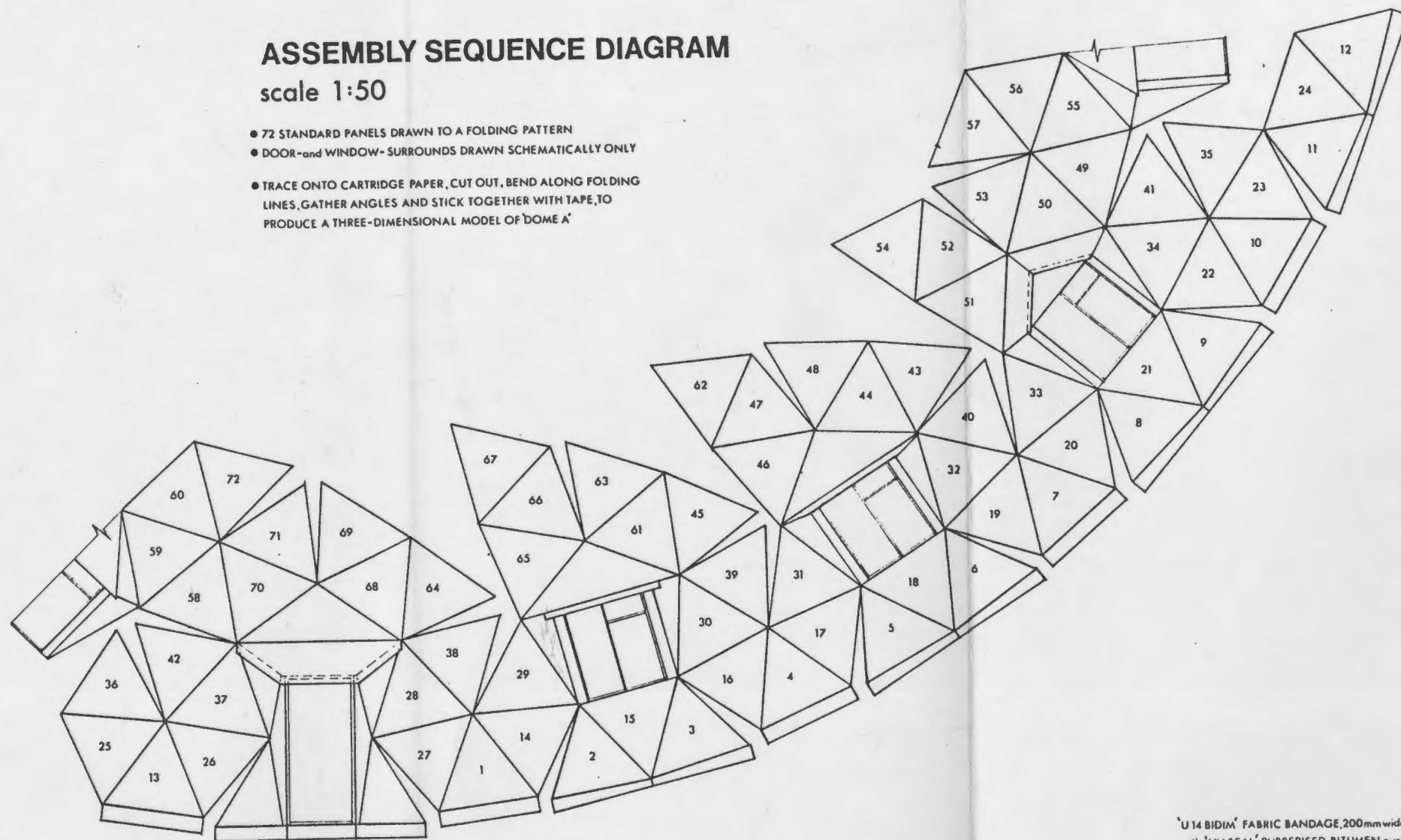
**DOME A**  
drawing no. 5  
**PANEL MANUFACTURING  
DETAILS**  
scale: given  
drawn by: p.waizenegger  
date: may 1984



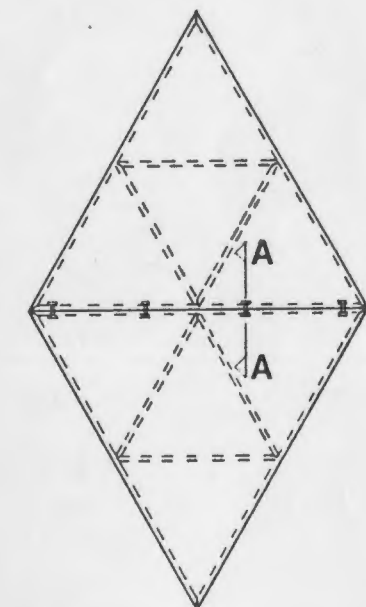
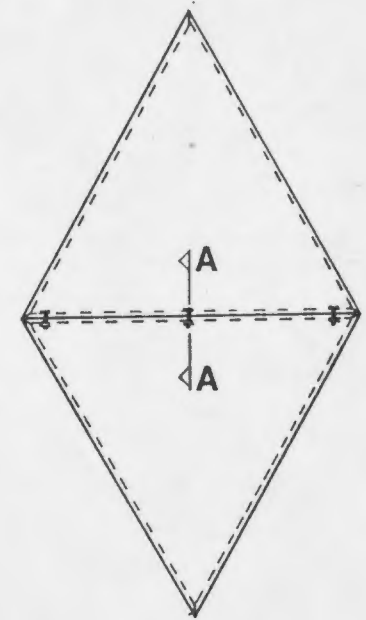
## ASSEMBLY SEQUENCE DIAGRAM

scale 1:50

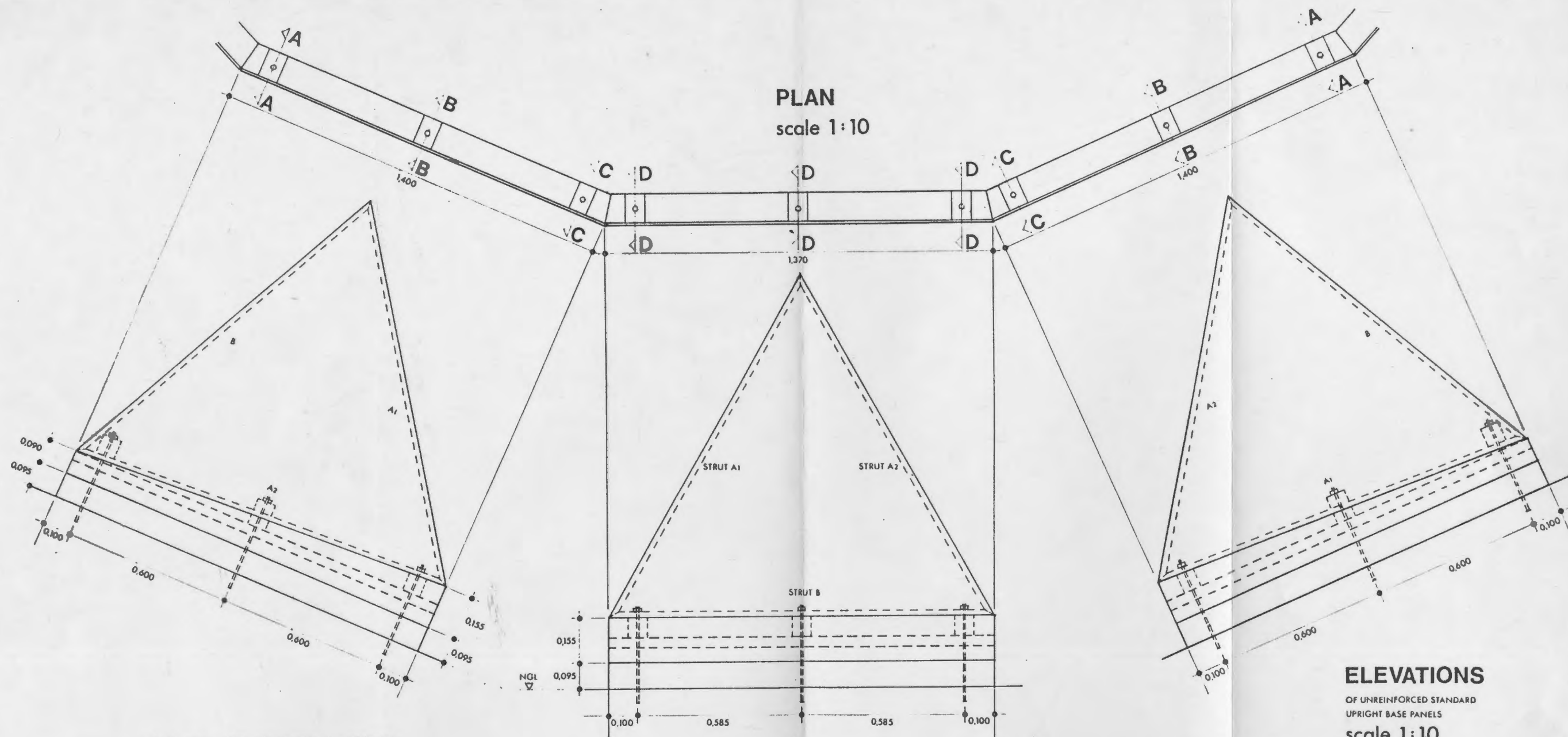
- 72 STANDARD PANELS DRAWN TO A FOLDING PATTERN
- DOOR- and WINDOW- SURROUNDS DRAWN SCHEMATICALLY ONLY
- TRACE ONTO CARTRIDGE PAPER, CUT OUT, BEND ALONG FOLDING LINES, GATHER ANGLES AND STICK TOGETHER WITH TAPE, TO PRODUCE A THREE-DIMENSIONAL MODEL OF 'DOME A'



**SECTION A-A**  
full size



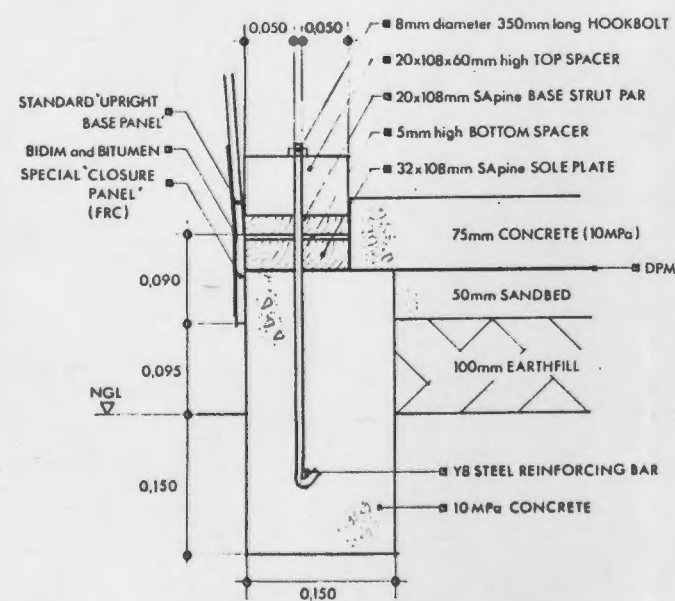
**DOME A**  
drawing no. 6  
**ASSEMBLY DETAILS**  
scale: given  
drawn by: pwaizenegger  
date: may 1984



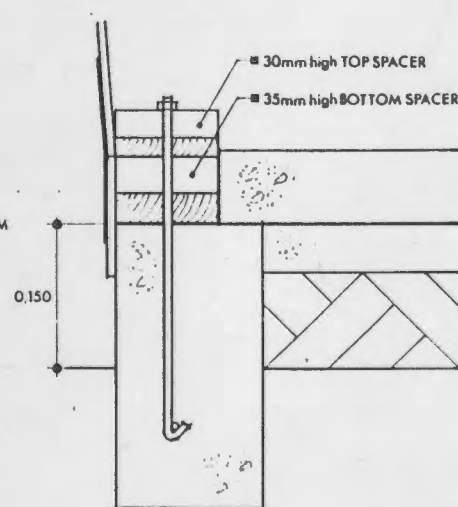
## ELEVATIONS

OF UNREINFORCED STANDARD  
UPRIGHT BASE PANELS

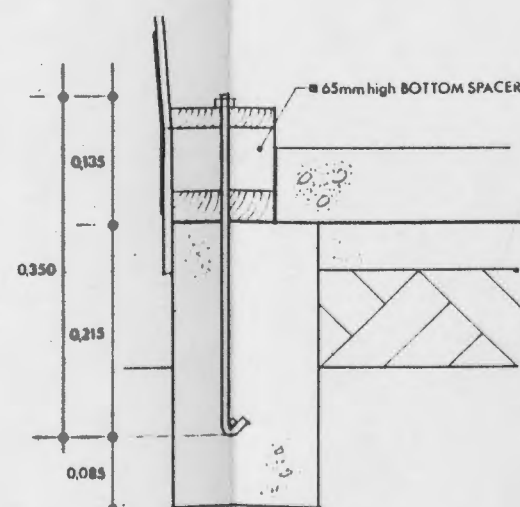
scale 1:10



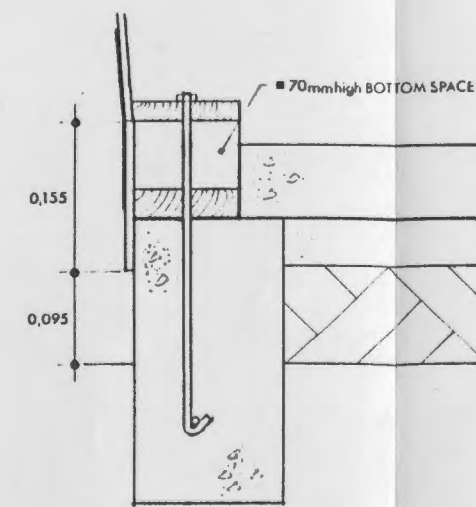
SECTION A-A; scale 1:5



SECTION B-B



SECTION C-C



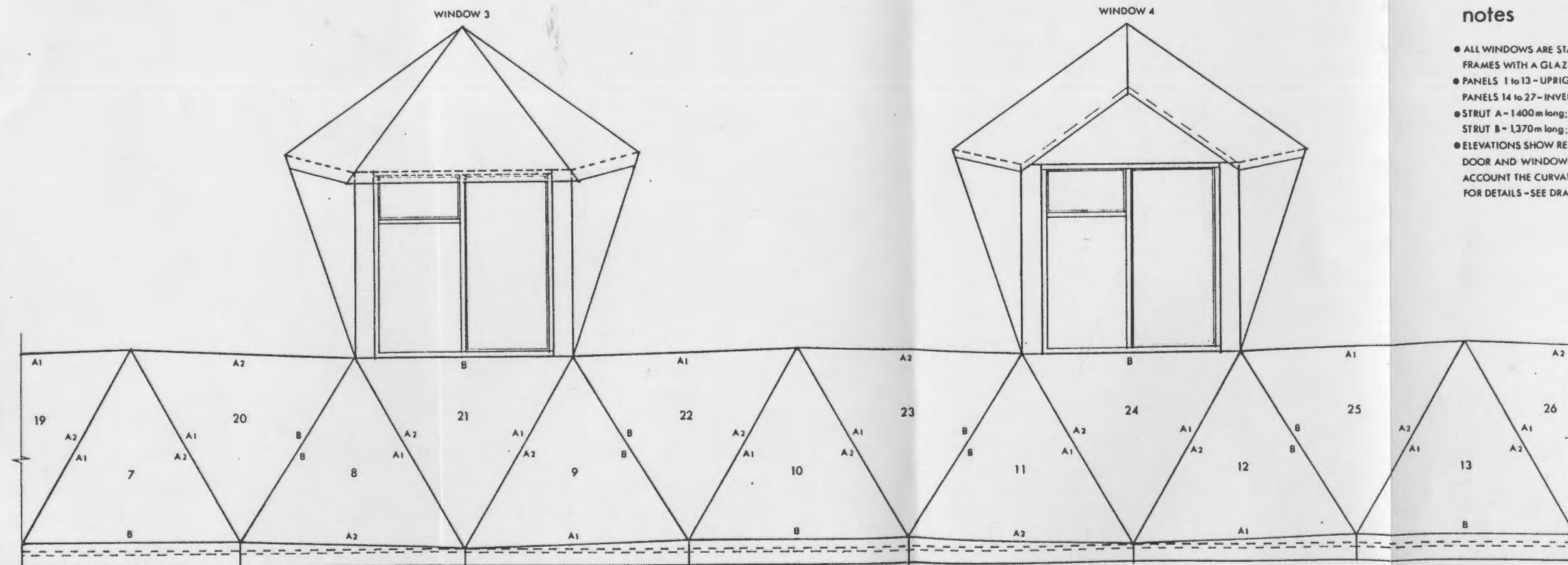
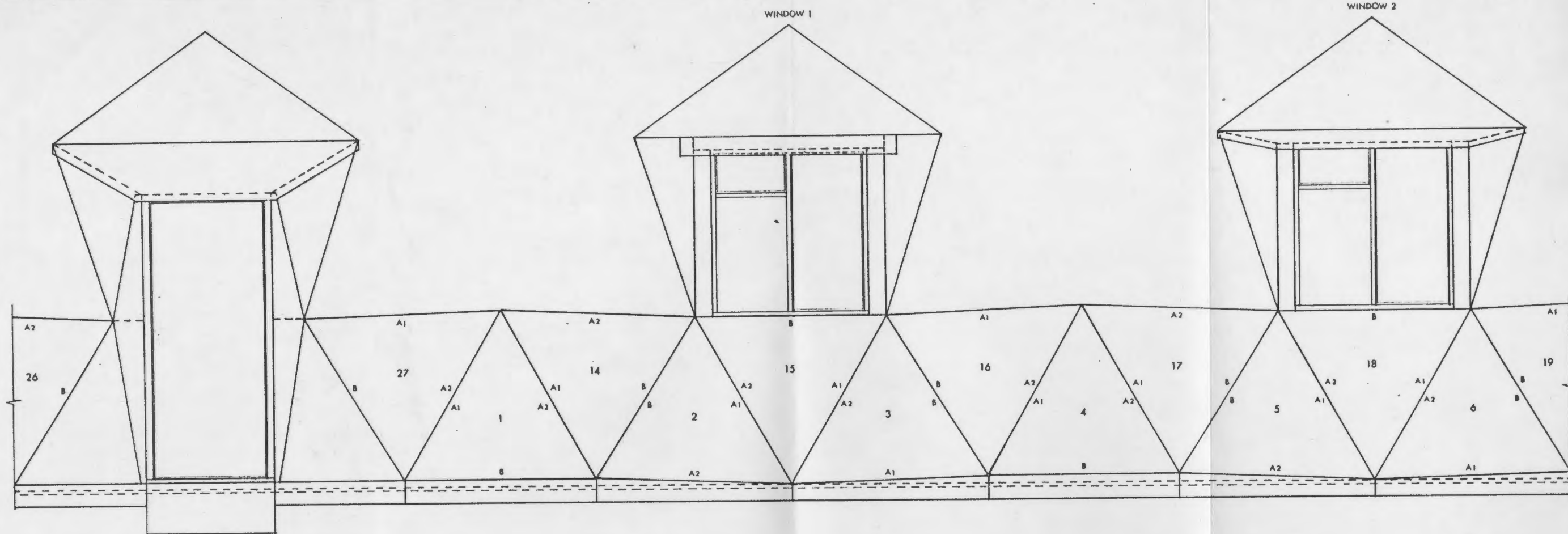
SECTION D-D

### NOTE:

ALL TIMBER IN CONTACT WITH CONCRETE MUST BE  
WRAPPED IN DPC OR PAINTED WITH CREOSOTE

**DOMA**  
drawing no. 7  
**ANCHORING THE DOME  
TO THE FOUNDATIONS**  
scale: given

drawn by: p.waizenegger  
date: may 1984

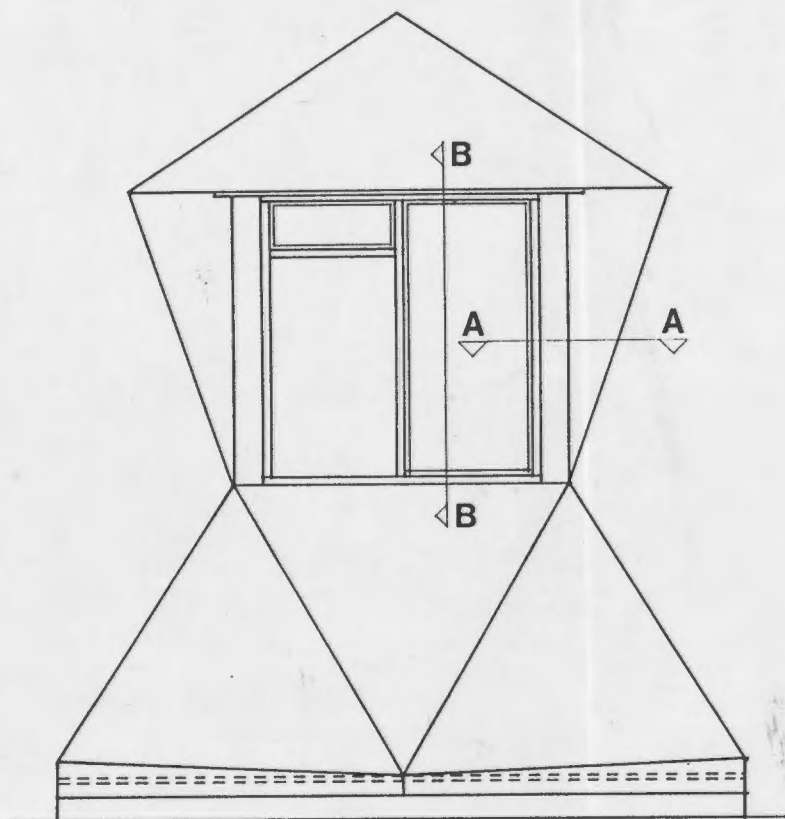


### notes

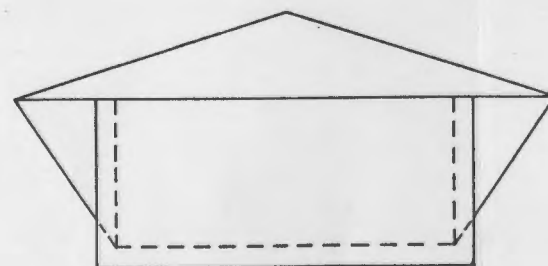
- ALL WINDOWS ARE STANDARD N43FX'WOODLYTE'TIMBER FRAMES WITH A GLAZING AREA OF 0.950m<sup>2</sup>
- PANELS 1 to 13 - UPRIGHT BASE PANELS  
PANELS 14 to 27 - INVERTED BASE PANELS
- STRUT A - 1400m long; A1 - blue; A2 - green  
STRUT B - 1370m long; red
- ELEVATIONS SHOW REAL STRUT LENGTHS i.e. STRUTS AROUND DOOR AND WINDOWS ARE NOT SHORTENED TO TAKE INTO ACCOUNT THE CURVATURE OF THE DOME SURFACE FOR DETAILS - SEE DRAWINGS no.9 and 10

**DOME A**  
drawing no.8  
**DEVELOPED**  
**ELEVATION**  
scale 1:20  
drawn by: pwaizenegger  
date: may 1984

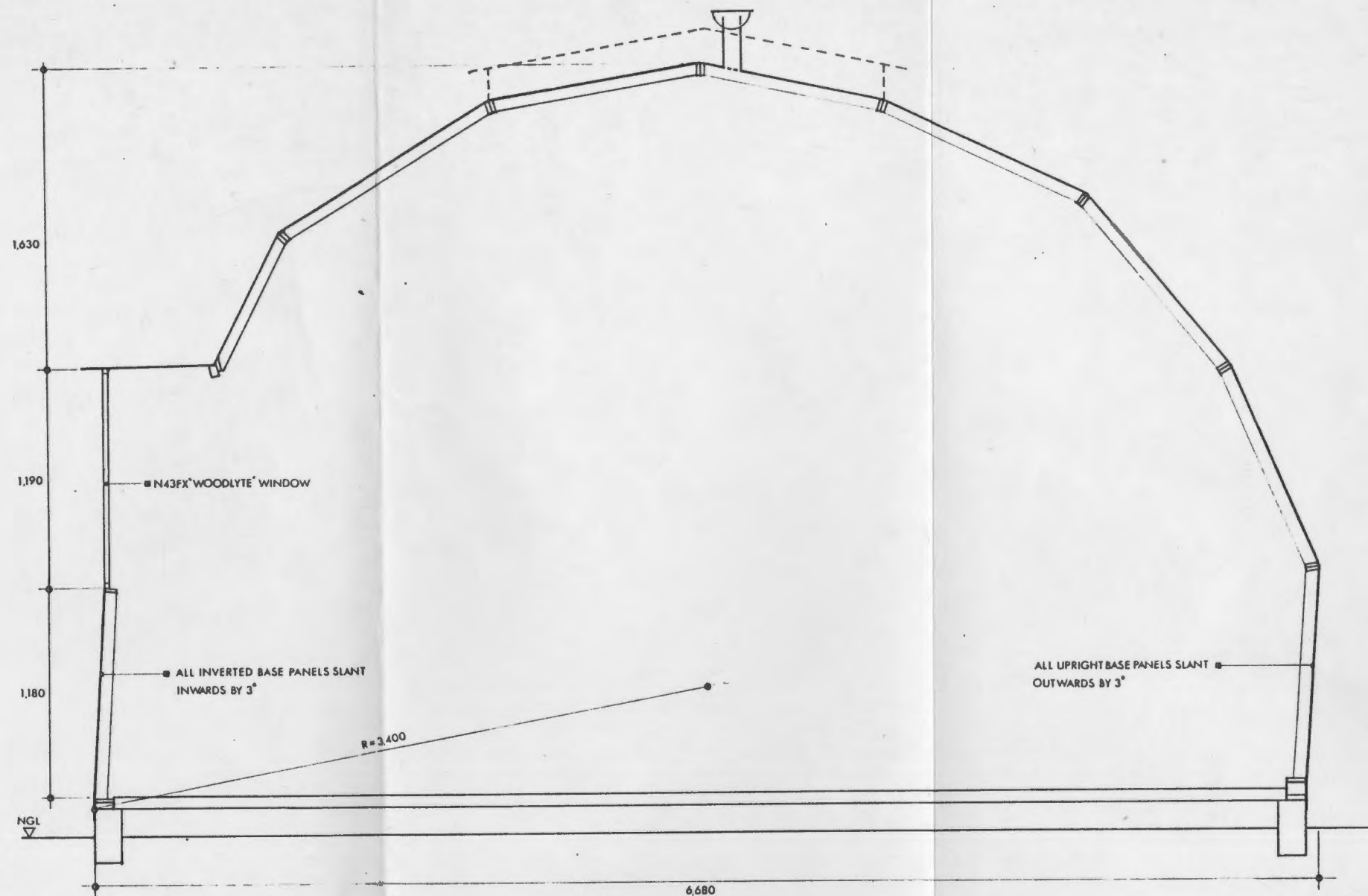




**ELEVATION**  
scale 1:20

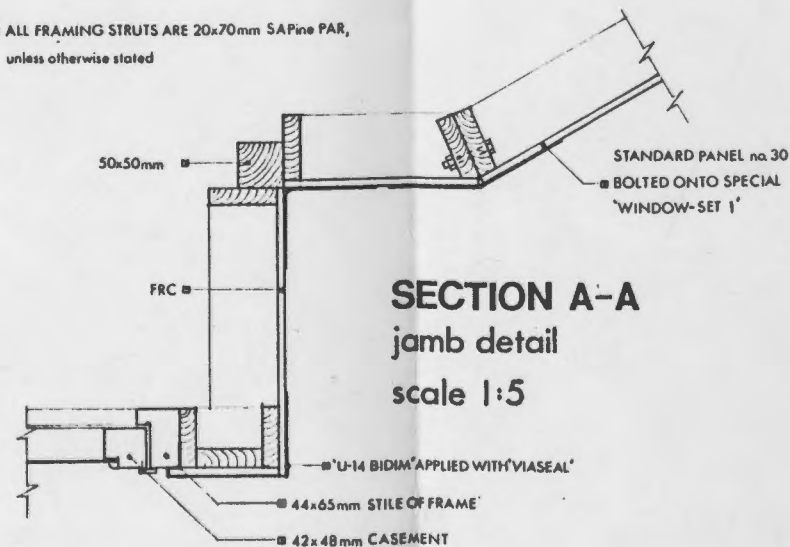


**PLAN**  
scale 1:20

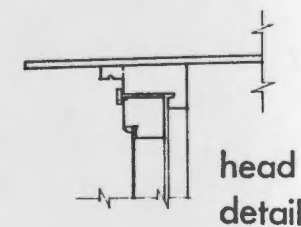


**CROSS-SECTION**  
scale 1:20

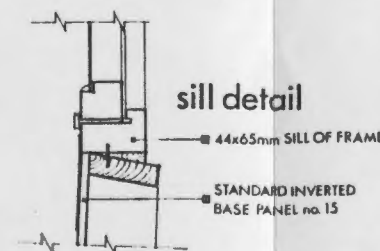
● ALL FRAMING STRUTS ARE 20x70mm SAPINE PAR,  
unless otherwise stated



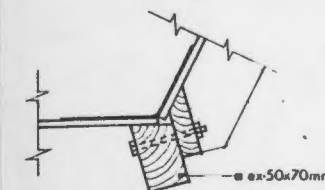
**SECTION A-A**  
jamb detail  
scale 1:5



head  
detail



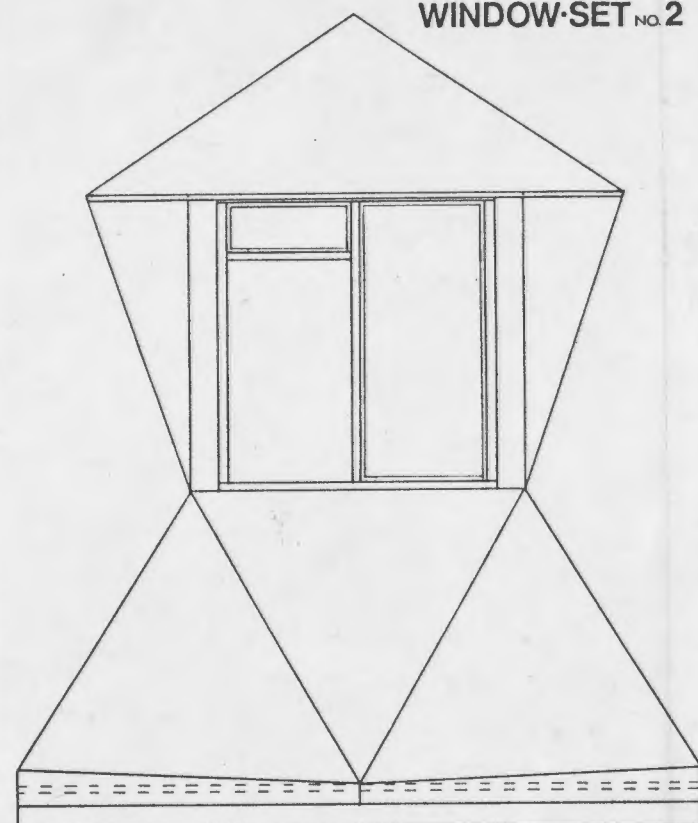
sill detail



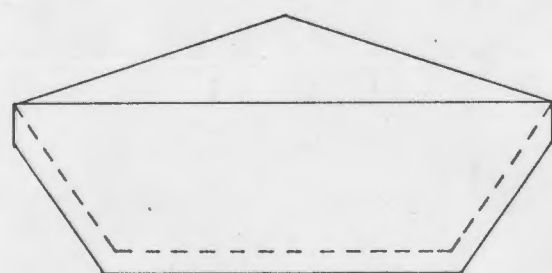
**SECTION B-B**  
scale 1:5

**DOME A**  
drawing no. 9  
**CROSS-SECTION AND**  
**WINDOW-SET NO. 1 DETAILS**  
scale: given  
drawn by: pwaizenegger  
date: may 1984

WINDOW-SET NO.2

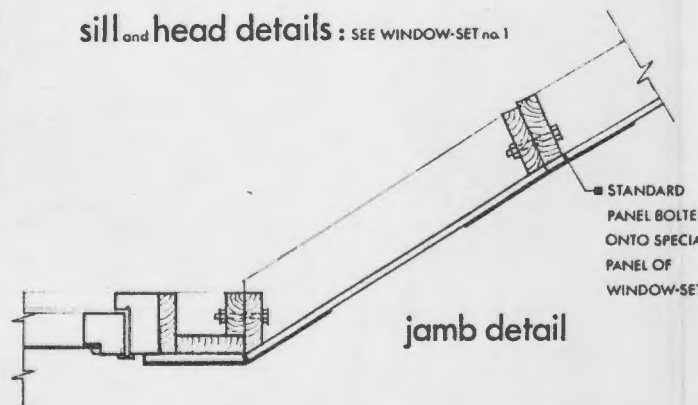


ELEVATION



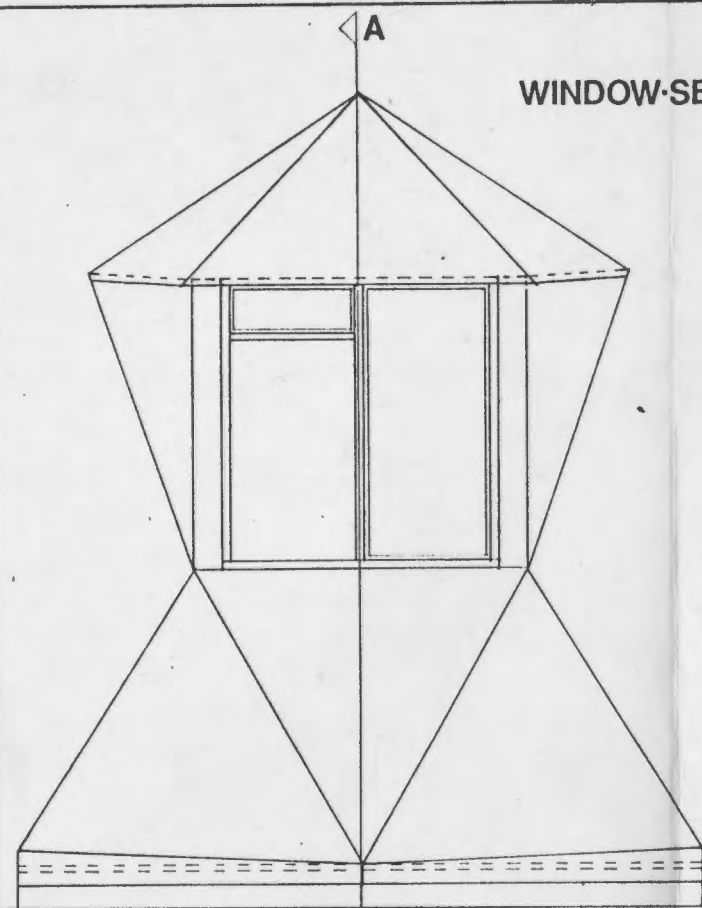
PLAN

sill and head details : SEE WINDOW-SET no.1

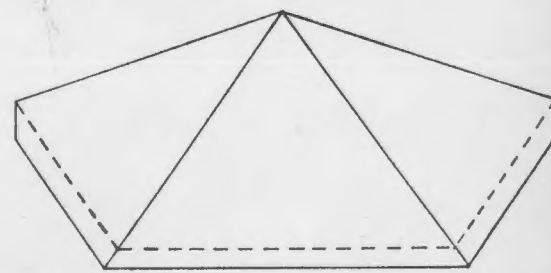


jamb detail

WINDOW-SET NO.3



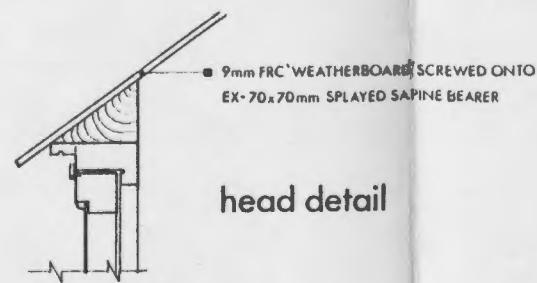
ELEVATION



PLAN

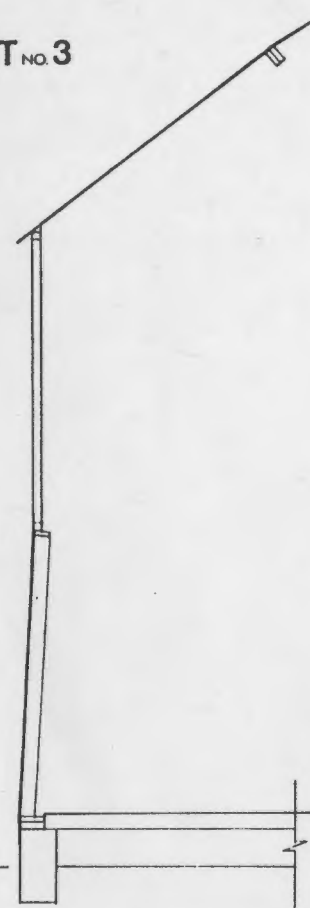
sill detail : SEE WINDOW-SET no.1

jamb detail : SEE WINDOW-SET no.2

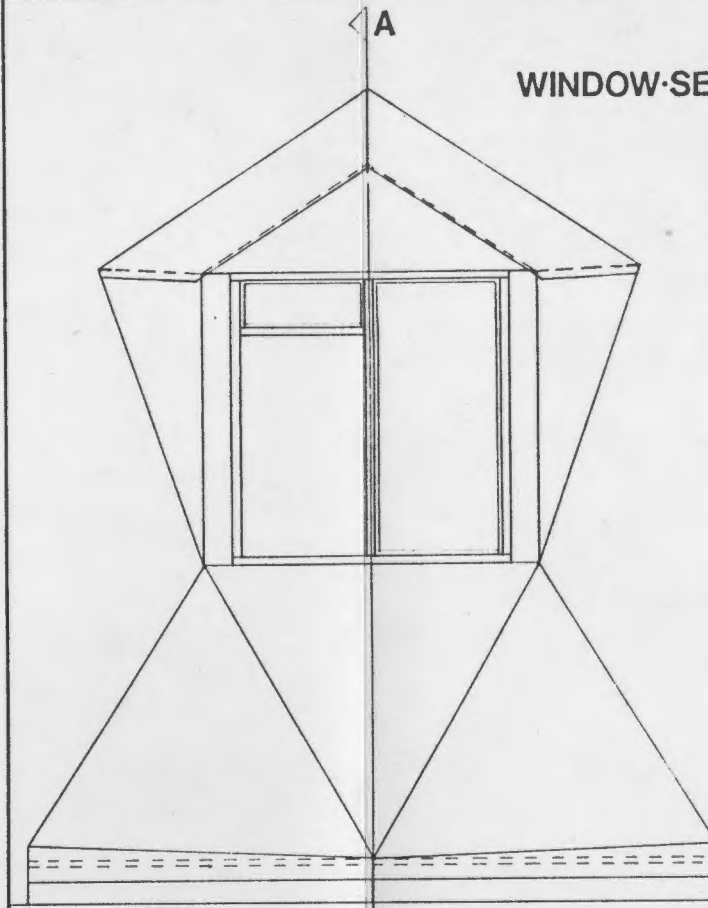


head detail

SECTION A-A



WINDOW-SET NO.4



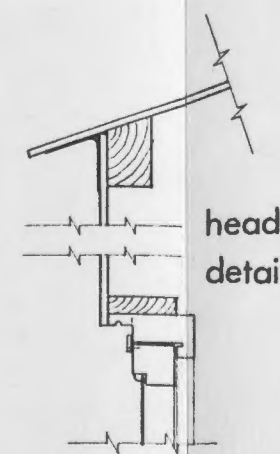
ELEVATION



PLAN

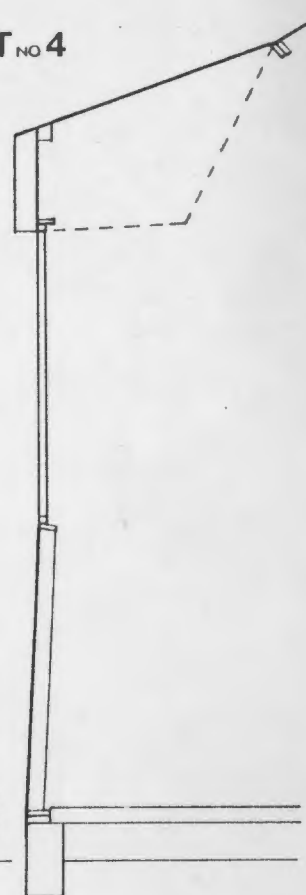
sill detail : SEE WINDOW-SET no.1

jamb detail : SEE WINDOW-SET no.2

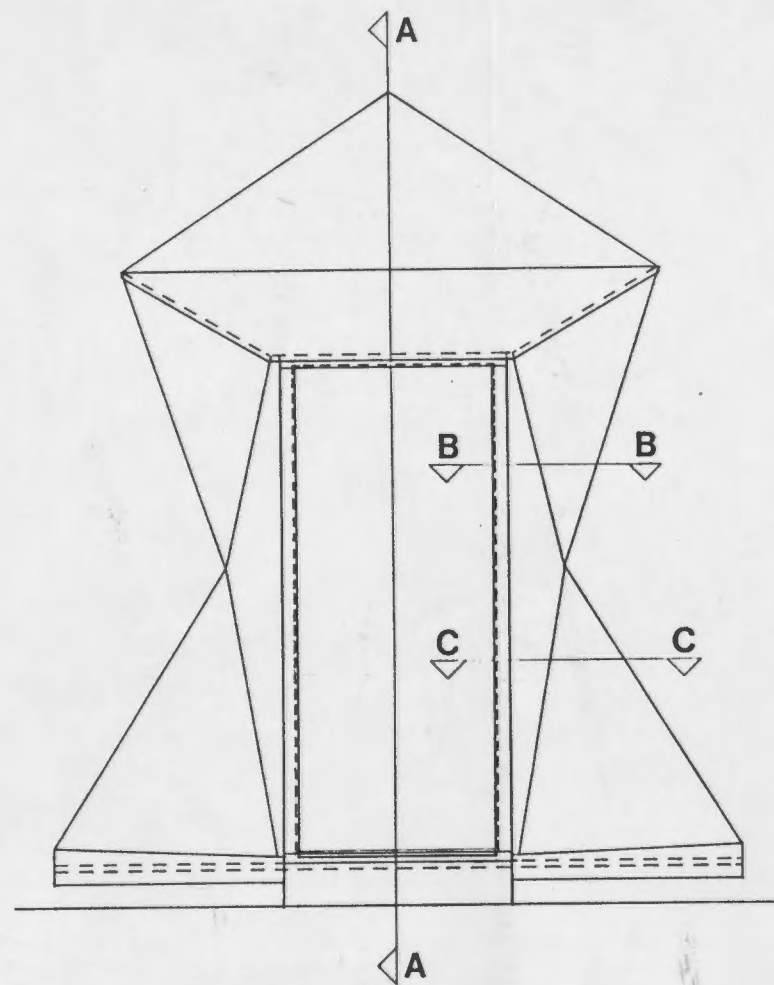


head detail

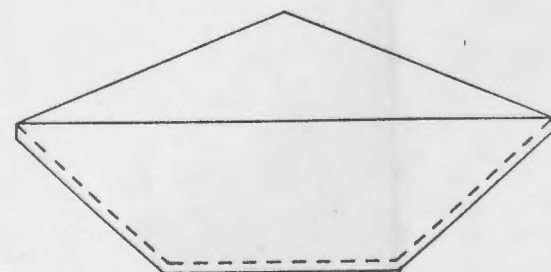
SECTION A-A



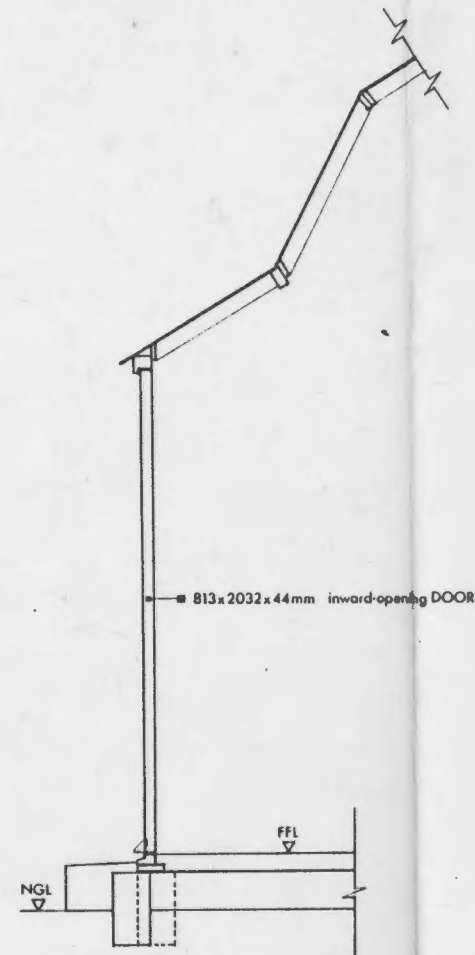
**DOMA A**  
drawing no. 10  
**WINDOW-SET NOS 2,3 AND 4**  
scale • details 1:5  
• plans, elevations, sections 1:20  
drawn by: p.waizenegger  
date: may 1984



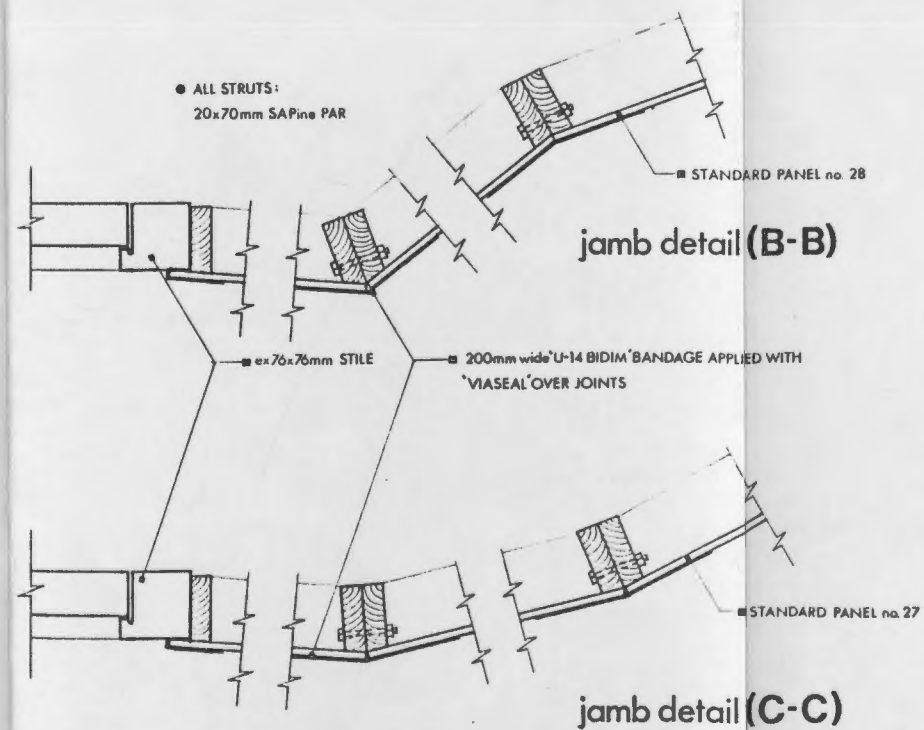
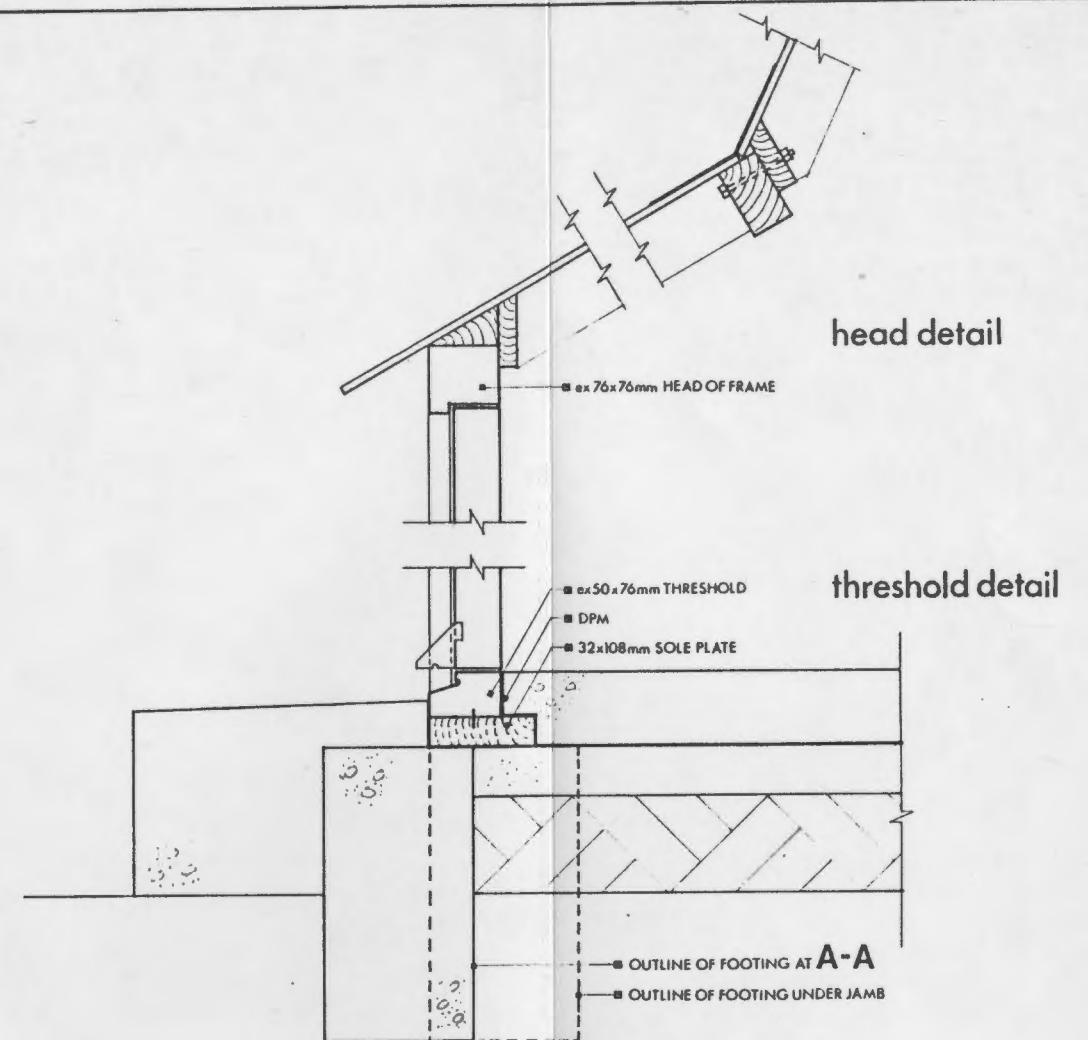
ELEVATION



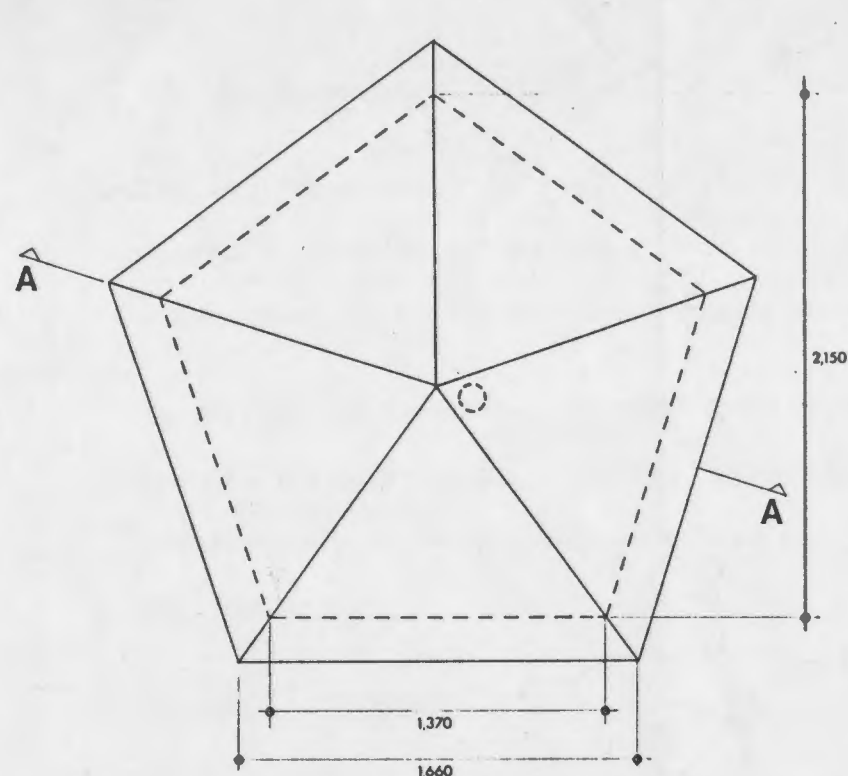
PLAN



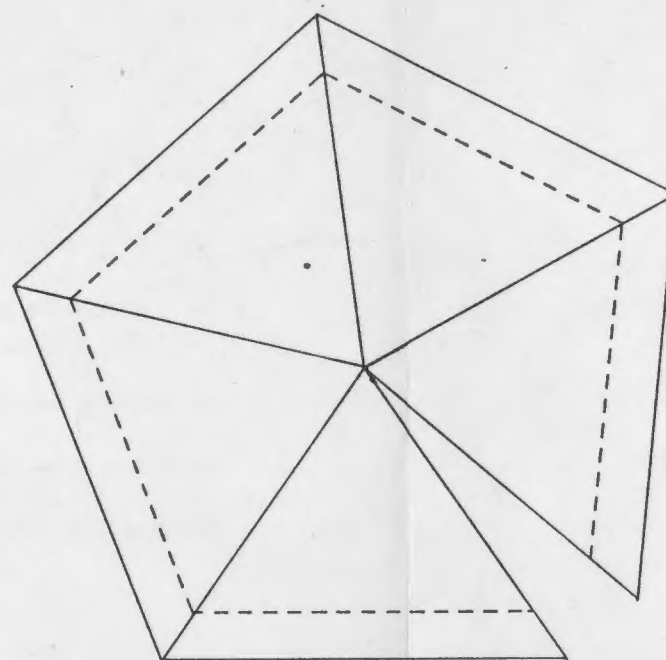
SECTION A-A



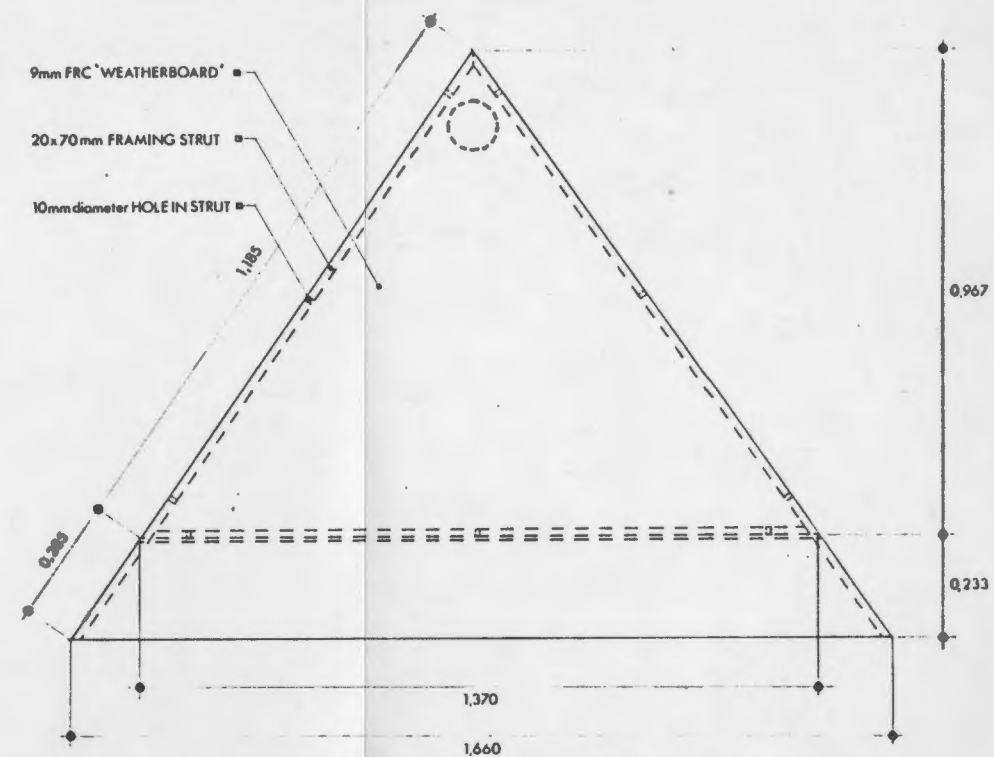
**DOME A**  
drawing no.11  
**DOOR-SET DETAILS**  
scale • details 1:5  
• section A-A elevation, plan 1:20  
drawn by: pwaizenegger  
date: may 1984



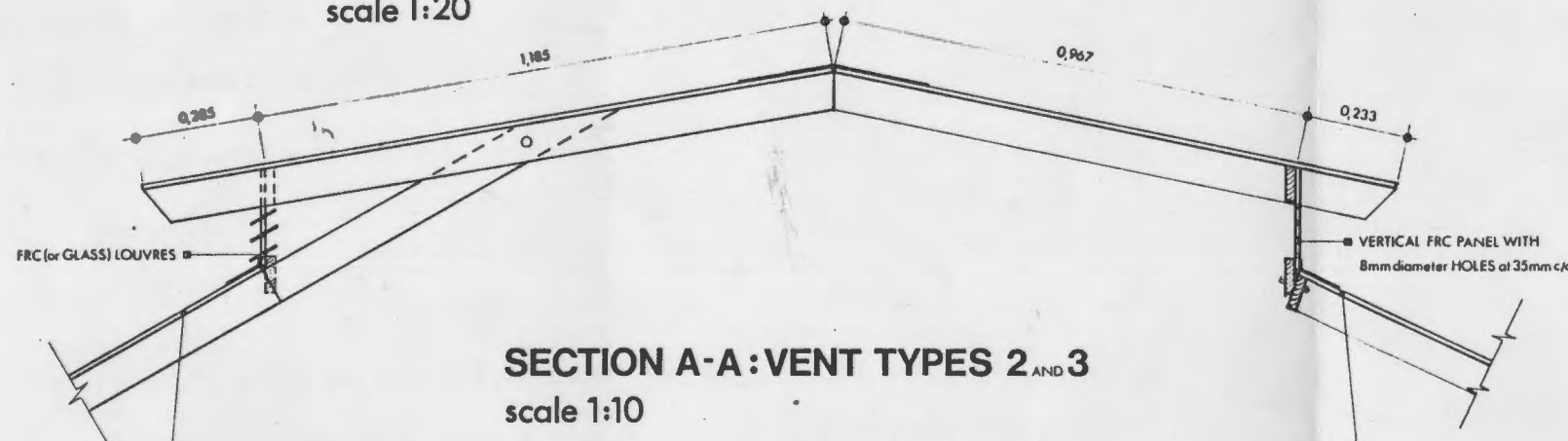
**PLAN**  
scale 1:20



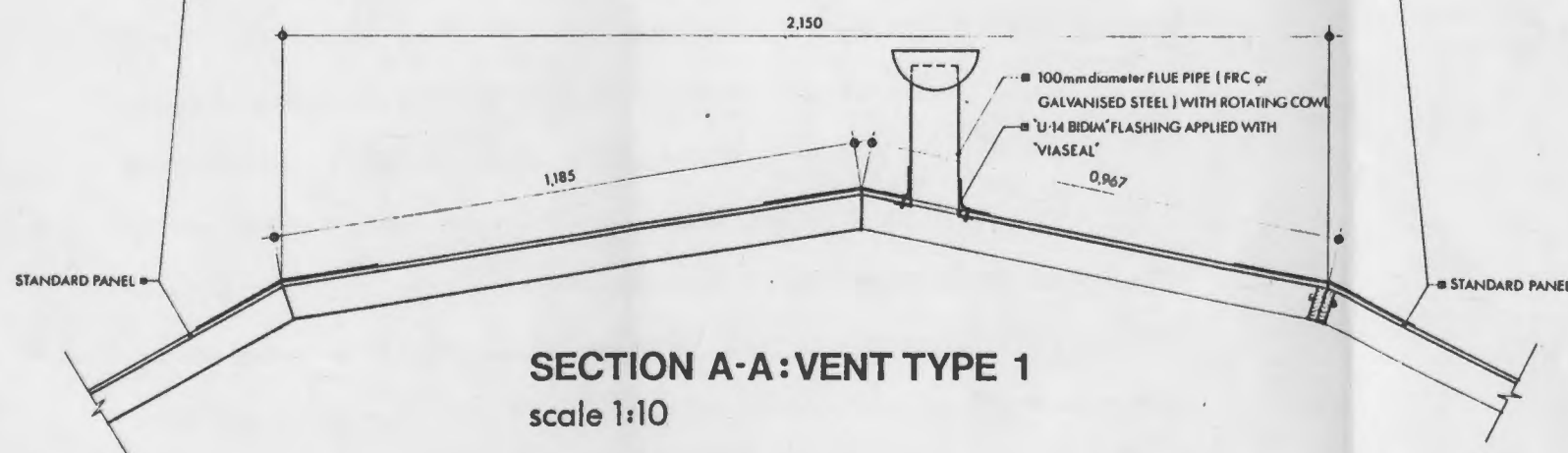
**DEVELOPMENT**  
scale 1:20



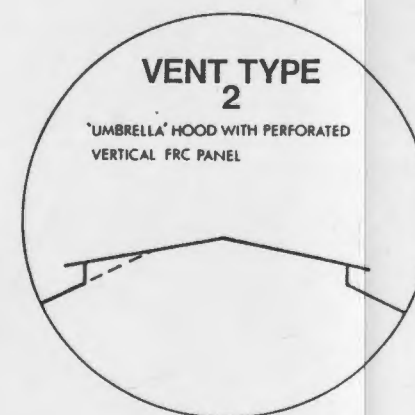
**VENT HOOD PANEL DETAILS**  
scale 1:10



**SECTION A-A: VENT TYPES 2 AND 3**  
scale 1:10

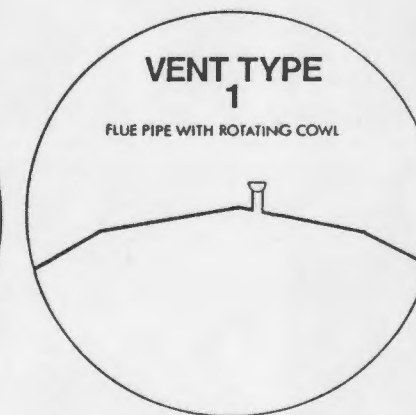


**SECTION A-A: VENT TYPE 1**  
scale 1:10



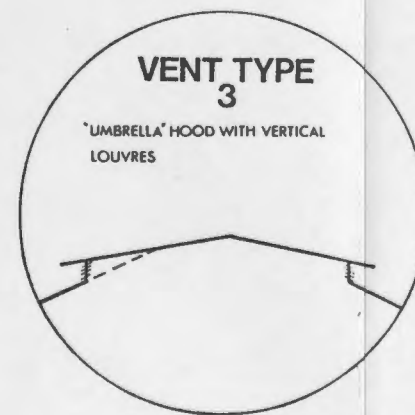
**VENT TYPE 2**

"UMBRELLA" HOOD WITH PERFORATED  
VERTICAL FRC PANEL



**VENT TYPE 1**

FLUE PIPE WITH ROTATING COWL



**VENT TYPE 3**

"UMBRELLA" HOOD WITH VERTICAL  
LOUVRES

scale 1:50

**DOME A**  
drawing no.12  
**VENTILATION DETAILS**  
scale: given  
drawn by: p.waizenegger  
date: may 1984



### 5.3 The Foundations

The first operation is to clear and roughly level the site. The area cleared is almost  $80 \text{ m}^2$  defining a circle 10 m in diameter - this provides a working space of 1,6 m around the outside of the proposed structure.

To set-out the foundations, a metal stake is driven into the ground at point O, the centre of the circle (see Figure 5.1). By means of a piece of inelastic string or nylon chord, a circle of radius 3,350 m (OA) is set-out from centre O.

**Figure 5.1: Setting-Out**

$$A_1 = 1,400 \text{ m}$$

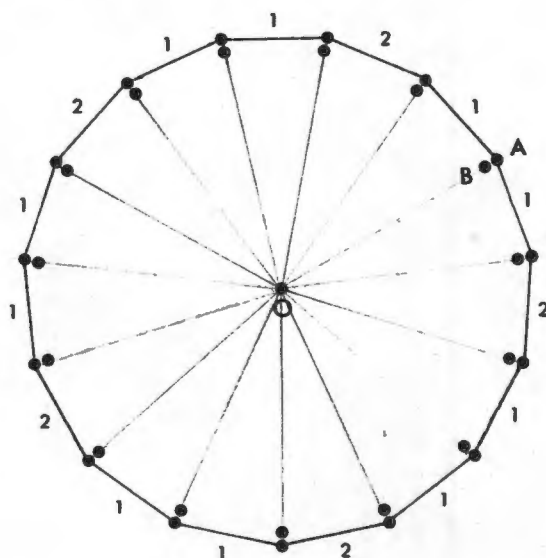
$$A_2 = 1,370 \text{ m}$$

$$\text{where } OA = 3,350 \text{ m}$$

$$B_1 = 1,330 \text{ m}$$

$$B_2 = 1,300 \text{ m}$$

$$\text{where } OB = 3,120 \text{ m}$$



From A, which defines the centre of the proposed door-opening, a chord-length  $A_1$  (1,400 m) is marked off, then chord  $A_2$  (1,370 m), then another  $A_1$ . This sequence is repeated five times to arrive back at A.

38x38 mm timber pegs, 500 mm long, are inserted at the fifteen points set-out, with pegs projecting approximately 150 mm above natural ground level (NGL). From the highest peg, which is exactly 150 mm above NGL at the highest point around the proposed foundations, an adjacent peg is levelled by means of a straight-edge and a spirit level or by means of a dumpy level. Continuing from peg to peg each one is successively levelled until the last peg, adjacent to the starting point, is level. Both the start-

ing peg and the last peg adjacent to it should be level and a measurement between the two serves as a check against a cumulative error in levelling. The spirit-level method can be very accurate and works well; however if deemed necessary, a dumpy level can be used as a check. When all thirty pegs are level, the 21x150 mm formboard of required length is nailed to the pegs - each length of formboard spans from the centre of one peg to the centre of an adjacent peg. The shutters are fixed with the top edge in alignment with the top of the level pegs. In case a peg has gone out of alignment, shutters should be checked at frequent intervals to ensure that they are level.

### 5.3 Foundation shutters



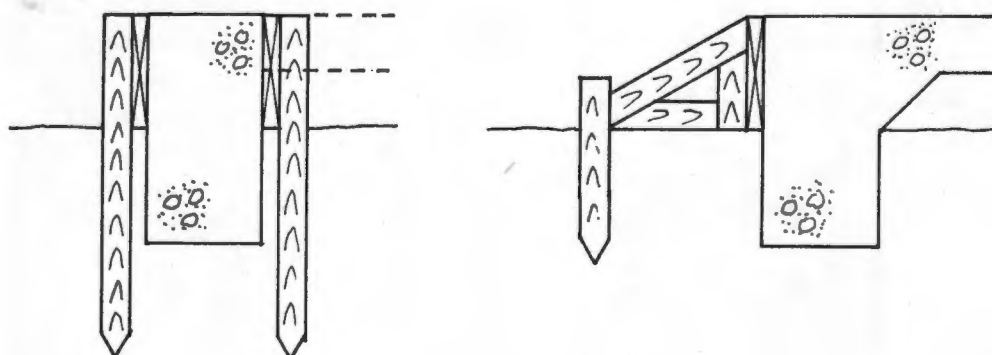
The process is repeated with radius 3,120 m (OB) to set-out another fifteen pegs marking chords  $B_1$ ,  $B_2$ ,  $B_1$ , five times returning to point B (see Figure 5.1 and Working Drawings Nos. 3 and 4).

When all thirty lengths of formboard are level, each 'pair' is supported at its centre-point with another 500 mm long timber peg (see Working

Drawing No. 4: Section A-A). A 'pair' of shutters implies two boards which are in alignment with each other and with the centre of the circle, one on the outside - and one on the inside - of the proposed foundation.

**NOTE:** The casting of concrete for footings and for the surface bed are two separate operations, because a damp proofing membrane is placed under the surface bed. Thus the footings are shuttered on both sides around the proposed foundations. However if a DPM is not required and is replaced by a layer of hardcore to prevent capillary moisture penetration through the floor, the construction of the foundations is greatly simplified with a concomitant saving in costs, because only one ring-shutter is required.

Figure 5.2 Shuttering Alternative



The trenches are excavated to the required depth (usually approximately 150 mm below the reduced NGL) between the two sets of shutters before cross-pieces, spanning across shutter 'pairs', are fixed - this allows for unobstructed digging.

The 38x38 mm sawn S.A. Pine cross-pieces are pre-drilled and must be accurately fixed to take the 8 mm-diameter holding-down hookbolts, which require a 50 mm concrete cover. Each 'pair' of shutters receives either three or four cross-pieces, depending on whether the 'upright base panels'



of the superstructure (see 5.4.1.2) are unreinforced or reinforced (see Working Drawings Nos. 4 and 5). When cross-pieces have been fixed, the 350 mm long hookbolts are inserted into pre-drilled holes and fixed such that they project 100 mm above the top of cross-pieces. A Y8 steel reinforcing bar is then tied on the hook of holding-down bolts to act as a tension ring around the foundation.

10 MPa concrete (19 mm stone; 50 mm slump) is then cast into trenches between shutters, compacted and struck off level with the top of shutters. Special care must be taken in compacting concrete around hookbolts and reinforcing bars, to avoid honeycombed concrete. Careful note must also be taken to ensure that hookbolts are not disturbed during the casting of concrete - the projection of each must be checked as the work proceeds.

The foundation beam is 21 m long - having a cross-sectional area of 0,045 m<sup>2</sup> (150x300 mm), the footing requires 1 m<sup>3</sup> of concrete (including 10 per cent for wastage).

Approximately twelve hours after casting, the concrete has set and hardened sufficiently for cross-pieces to be carefully removed. The inside set of shutters may also be removed so that the floor construction can proceed; however, the outside forms should left in place for at least three days.

The solid floor is of conventional construction - a layer of earthfilling and a 50 mm sandbed, levelled and compacted, a sheet of USB green damp proofing membrane and a 75 mm surface bed of 10 Ma concrete, which is compacted and struck-off level. Approximately two hours after casting concrete, the surface bed may be power-floated to a smooth finish so as to avoid the necessity for a screed when the floor finish is laid.

## 5.4 The Superstructure

The geodesic dome can serve either as a complete structure or simply as a roof, with 'riser walls' providing support - either a dome or a dome-on-cylinder. Dome A completely encloses a floor area of 35 m<sup>2</sup> without 'riser walls' - the dome superstructure is thus connected and anchored directly to the foundations. The construction of the dome falls within two distinct stages:

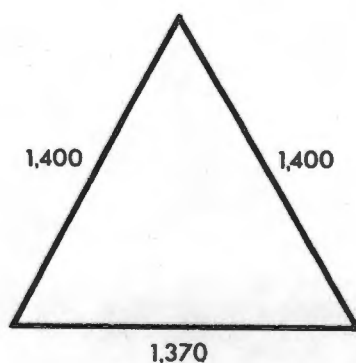
- Manufacture
- Erection or assembly

Being a 'panel dome', the major portion of construction falls within the process of manufacture. The accuracy achieved in the manufacture of pre-fabricated panels determines the ease with which the erection process can be executed. Under a constant factory environment with good workmanship, the correct tools and adequate supervision, extreme accuracy is possible. This is one of the major advantages over brick 'riser wall' construction, which involves specialised and time-consuming on-site operations. However manufactured riser-walls, as used in conventional timber-framed housing, are a feasible alternative, although the essence of geodesic structuring is no longer strictly applied.

### 5.4.1 'The Standard Shell'

The 'Standard Shell' of Dome A consists of 72 identical triangular panels of the following dimensions:

Figure 5.3



#### 5.4.1.1 Manufacture of 'Standard Shell' Panels

NOTE: 'Standard Panels' are assumed to be unreinforced unless otherwise stated (see Working Drawing No. 5).

##### Material requirements:

- \* 20x70 mm S.A. Pine PAR: 1,400 m long (A) - in No. 136  
1,370 m long (B) - in No. 67
- \* 20x108 mm S.A. Pine PAR: 1,400 m long - in No. 8  
1,370 m long - in No. 5
- \* 9 mm fibre-reinforced cement (FRC) 'weatherboard' unpressed flat sheet panels cut to the required triangular shape - in No. 72
- \* 3,2 mm-diameter (8 guage), 40 mm long brass screws - in No. 1500
- \* 1 litre Resorcenol glue or Cascamite glue

##### Tool requirements:

- \* Radial arm saw
- \* Drill press
- \* Drill bits (4-, 5-, 8-, and 10-mm-diameter)
- \* Tape measure
- \* 'Yankee' screw driver

All timber struts are stacked in three piles and colour-coded as follows:

##### 20x70 mm struts:

- A<sub>1</sub> - 1,400 m long: Blue; in No. 68
- A<sub>2</sub> - 1,400 m long: Green; in No. 68
- B - 1,370 m long: Red; in No. 67

##### 20x108 mm struts:

- A<sub>1</sub> - 1,400 m long: Blue; in No. 4
- A<sub>2</sub> - 1,400 m long: Green; in No. 4
- B - 1,370 m long: Red; in No. 5

NOTE: In the original dome all panels were unreinforced; however, in reconstruction, all base panels were reinforced (13 upright panels and 14 inverted panels). The reinforcing struts are 38 x 38 mm sawn S.A. Pine and the following are required:

- A<sub>1</sub> - 0,670 m long: Blue; in No. 27
- A<sub>2</sub> - 0,670 m long: Green; in No. 27
- B - 0,655 m long: Red in No. 27

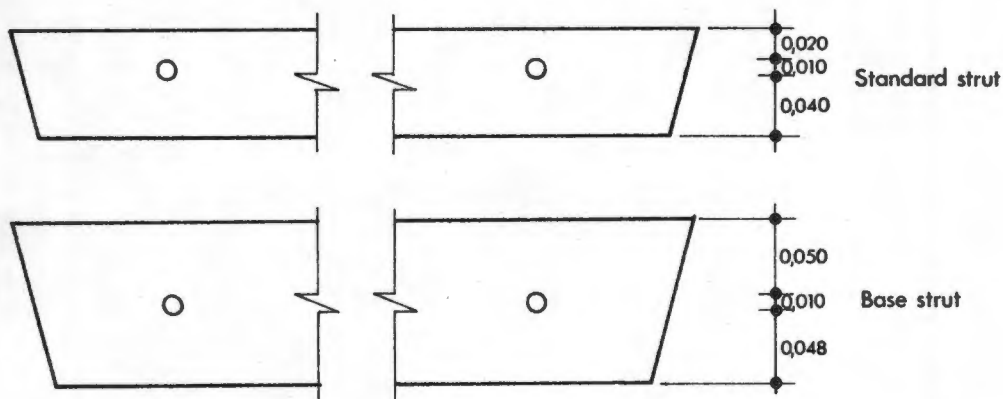
Struts are now angle-cut and drilled according to the 'shop-drawings' for Dome A. This is an extremely time-consuming operation, especially the bevel-cutting or 'ripping' of struts. The splay- and mitre-cuts are compounded in a jig (see 4.2.1.1) - care must be taken to ensure that compound angles are cut accurately!

NOTE Struts  $A_1$  and  $A_2$  are of equal length, but in angle-cutting  $A_1$  is a 'left' strut and  $A_2$  is a 'right' strut.

Each strut receives three 10 mm-diameter holes to take the 8 mm-diameter bolts during erection - there is a 2 mm variance to allow for a slight disalignment of holes during erection. If panels need to be triangularly reinforced for additional impact strength, each strut has four bolt-holes (see Working Drawing No. 5).

There are thirteen 'upright base panels' (see 5.4.1.2) which are fixed to the foundations by means of the hookbolts projecting from the concrete footing. The 'base strut' of each of these panels is a 20x108 mm timber which is drilled such that the position of the holes aligns perfectly with the hookbolts. In effect these base struts are drilled in exact accordance with the sole plate. Of the thirteen panels, four have strut  $A_1$  as their base strut, four have strut  $A_2$  and five have strut B. These thirteen base struts are drilled 50 mm from their outside edge to allow for a minimum concrete cover around hookbolts, whereas all other struts receive holes which are 20 mm from the outside edge or 40 mm from the inside edge (see Figure 5.4). Standard struts are thus not drilled down their centre-line, because by having fixing points between adjacent panels closer to the outside edge, thus closer to the covering panel, the strength of the dome is considerably increased.

**Figure 5.4** Strut Drilling Details

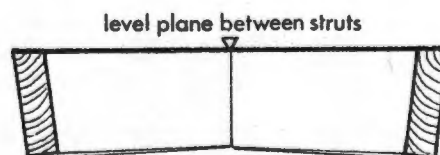


**NOTE:** The base strut of each upright base panel is a larger timber than the other struts so that splitting of struts around hookbolts, caused by tensile stress at this point, is avoided.

After angle-cutting and drilling, struts are again stacked in their respective colour-coded piles.

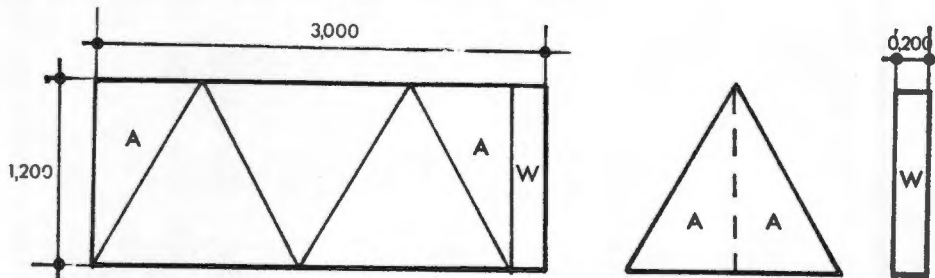
Triangular timber frames are now manufactured in a jig, using one strut from each pile per frame. Great care must be taken to ensure that struts are correctly positioned in the jig, with  $A_1$  on the left,  $A_2$  on the right and B at the bottom of the triangle. Check that the 'ripped' edge always runs along the top edge of the struts. If angle-cutting has been accurately executed, the top edge of the three struts of each frame should line up in a plane. Struts are drilled, glued and screwed twice at each vertex of the triangular frame. Alternatively industrial stapling may be used to save time and money.

**Figure 5.5** Correctly Manufactured Panel



Completed timber frames are covered with 9 mm FRC 'weatherboard' unpressed flat sheet panels, pre-cut to the required 'standard' size. Since all cladding panels are triangular, the cutting of panels from standard rectangular FRC sheets may result in substantial wastage.

For DOME A, 1,200m x 3,000m FRC sheets were used and triangular panels were cut-out as follows:



Almost 30% of each sheet is wasted unless the offcuts are patched together with 'Bidim' U-14 and rubberised bitumen to form another triangular panel. Thus wastage of FRC cladding is reduced to less than 7%. Alternatively, the offcuts may be used for special panels around the door and windows.

Each panel has twenty-one pre-drilled 4 mm-diameter holes (seven per edge), 12 mm from the edge of the panel to take the 8 x 40 mm brass screws, which are used to fix the FRC panels to the timber frame. A nailable FRC flat sheet was recently put on the market - this will inherently result in substantial cost- and time-savings.

Having completed the manufacture of the 72 'standard panels', the 'standard kit' is ready for assembly.

It has been mentioned that the impact resistance of cladding panels, both FRC and plywood, is questionable. Thus for greater impact strength the panels may be reinforced with timber struts, which subtriangulate the frames. These reinforced panels are fixed to adjacent panels with four bolts per edge, not three bolts as with unreinforced panels. Two reasons for this are, firstly, that the panels are slightly heavier than before, and secondly, that the reinforcing struts meet the framing struts at the mid-point of the latter, where unreinforced panels have a fixing bolt (see Working Drawing No.5).



#### 5.4 Panel manufacture



#### 5.5 Ditto





#### 5.4.1.2 Assembly of 'Standard Shell'

On-site assembly is an extremely simple process. Each panel is light enough to be handled by one person and it takes two people approximately eight hours to erect the entire 'standard shell'.

The first operation in erecting the superstructure is to place the 32x108 mm sole plate. There are fifteen sole plates of the following lengths:

- A - 1,400 m long; Blue; in No. 10
- B - 1,370 m long; Red; in No. 5

Each sole plate length is angle-cut at both ends and pre-drilled to take the hookbolts projecting from the foundation.

#### 5.6 Foundations and sole-plate



When the sole plate has been positioned, the 'upright base panels' (Panels 1 to 13: see Working Drawings Nos. 6 and 7) are placed. These panels do not sit flat on the horizontal sole plate. This slightly uneven cut-off plane occurs in any vertex-zenith orientated icosahedron-based geodesic dome (a feature of Dome B, a 3-frequency 'truncatable' alternate design, is that it sits flat on both a 3/8- and 5/8-sphere cut-off plane: see 6.1).

In order to accommodate this uneven cut-off plane, timber spacers are required at each hookbolt. Working Drawing No. 7 shows that those upright base panels having strut B as base strut sit horizontal with respect to the sole plate, but 70 mm above the plate - thus at each hookbolt along this strut a 70 mm high 'bottom' spacer is required. Each upright base panel having strut A ( $A_1$  or  $A_2$ ) as base strut slopes with respect to the sole plate at an angle of approximately  $3^\circ$ , being 70 mm above the plate at one end and flush on top of the plate at the other end. Since all hookbolts project 132 mm beyond the top of the plate, both 'bottom' and 'top' spacers are necessary. Note that one pair of 'bottom' and 'top' spacers, required per hookbolt, can be made out of a standard 70 mm high spacer.

All 'bottom' spacers must be correctly positioned over hookbolts before upright base panels are positioned. 'Top' spacers are placed over hookbolts onto sloping base struts once panels have been positioned - then hookbolt-nuts are tightened.

|   |
|---|
| <p>NOTE: For an alternative method of supporting upright base panels see 5.4.2.1.</p> |
|---|



### 5.7 Foundations and sole-plate and spacers



### 5.8 Ditto





'Inverted base panels' are slotted in between two adjacent upright base panels and are fixed with four bolts along each edge. Panels 14 to 25 are inverted base panels, as are panels 26 and 27, which are fixed on either side of the door opening and are temporarily supported until 'door specials' are fixed (see 5.4.2.3).

Panels 28 to 72 are now assembled in exact accordance with Working Drawing No. 6. When Panel 54 has been fixed, the first great circle arch is complete and the structure assumes self-stability. The top panels around the proposed 'vent hood' are almost 4,000 m above the floor - thus scaffolding is required to fix panels 43 to 72.

**NOTE:** • As panels are assembled, nuts should not be fully tightened, because as the dome 'grows', it moves in the most inconceivable places - only when the final 'standard panel' has been fixed, does the dome settle into a stress equilibrium and all nuts can be fully tightened.

- The numbering of panels in the photographs does not correspond with Working Drawing No. 6 (see 5.2: 'Notes on Working Drawings').

#### 5.10 Reinforced inverted base panels and some unreinforced 'standard' panels





5.11 First great circle arch complete



5.12 Ditto





5.13 'Standard shell' assembly continued



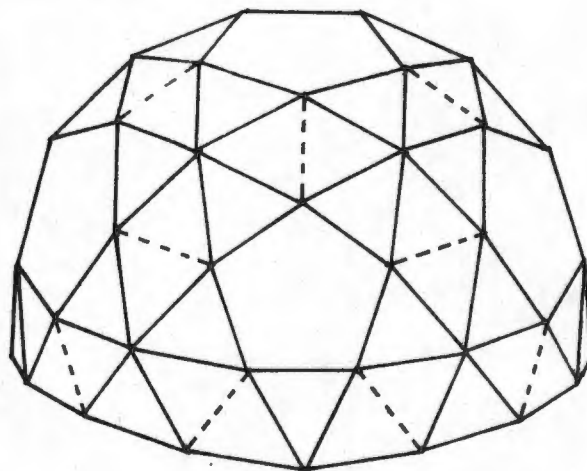
5.14 'Standard shell' completed



There are a number of unique features about the 'standard shell' of Dome A:

- The 3-frequency icoso-alternate breakdown results in great circle bands similar to those defined by the Burmese toy ball, which inspired Fuller's conception of the 'Indhlu' geodesic dome in 1958.

Figure 5.6    Great Circle 'Bands' of Panels

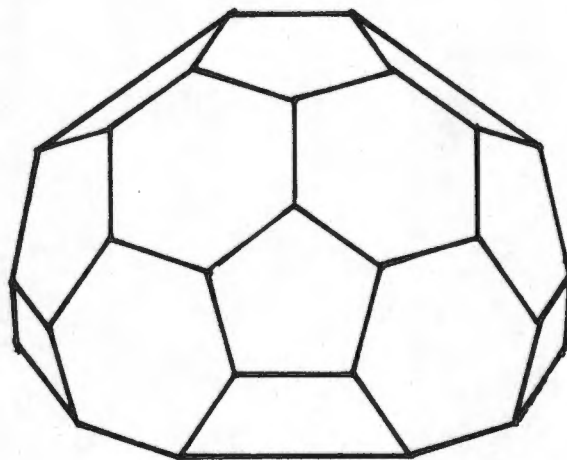


The  $5/8$ -sphere cut-off plane of Dome A results in five great circle arches which are horizontally braced and buttressed by one great circle band around the base of the dome. There are six pentagonal openings in the resultant structure, which are utilised to accommodate the 'special panels', one serving as a door opening, four as windows and one, at the apex, as a ventilation opening. The 'Indhlu' geodesic dome was identically subdivided with the 'standard shell' consisting of interwoven great circle sheets of corrugated aluminium (see Chapter 3).

- Dome A could be substantially simplified by truncating the icosahedron so that the 'standard shell' defines ten regular hexagons and four half-hexagons, instead of 72 triangles. The manufactured

hexagonal flat panels would have to be triangularly reinforced with timber struts - in effect each hexagonal panel consists of six triangular divisions.

Figure 5.7 Truncated Icosahedron



- Dome A only has one panel size making up the complete 'standard shell' - any other 3-frequency or higher frequency-modulated design results in at least two 'standard' panels.
- The 3-frequency alternate breakdown, according to which Dome A is designed, in its complete spherical form, has 92 vertexes, analogous with the 92 chemical elements in nature (see Appendix B.4).

#### 5.4.2 'Special Panels'

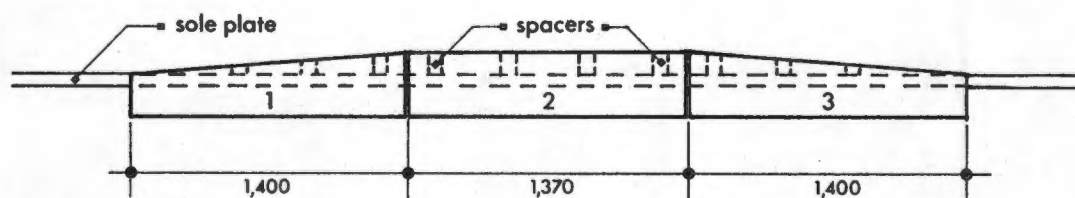
'Special panels' are grouped as follows:

- 'Closure' panels
- 'Window' panels
- 'Door' panels
- 'Ventilation' panels

### 5.4.2.1 'Closure' Panels

This set of panels is required to close off the gap left by the upright base panels which do not sit flat on the sole plate (see 5.4.1.2). Three different panel-shapes are required, although two are similar, the one being a 'left', the other a 'right'.

Figure 5.8 'Closure' Panels (see also Working Drawing No. 7)

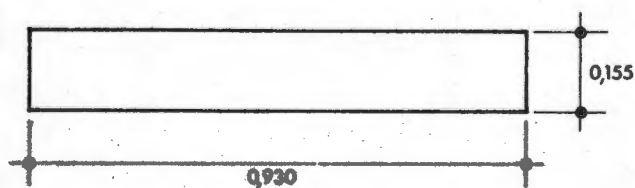


Number of panels required:

- Four of panel 1
- Five of panel 2
- Four of panel 3

Two closure panels, a 1 and a 3, are left out at the door opening, where panels similar to 2, but smaller, are required.

Figure 5.9 Special 'Closure' Panels at Door Opening



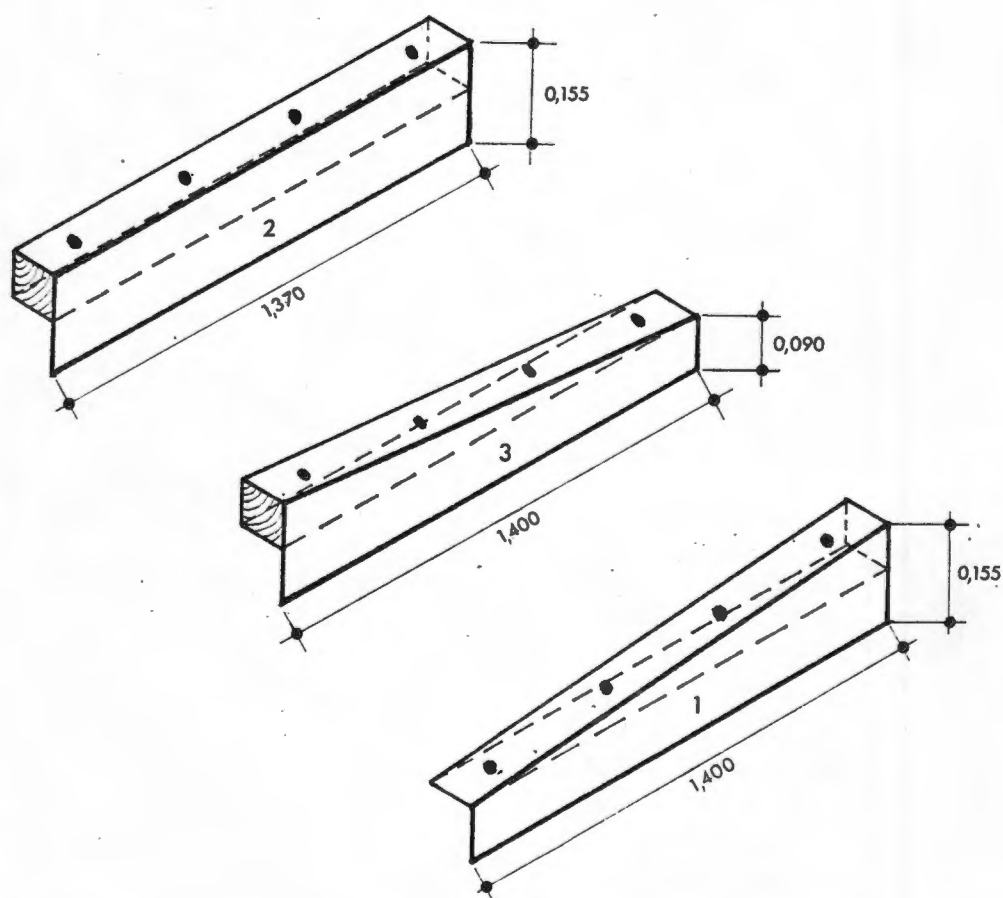
The use of individual spacers, as in Dome A, is a rather laborious method of supporting upright base panels. The major disadvantage is that the gaps left between spacers must be closed-off on site. The FRC 'closure' panels are not fixed to the timber frame during manufacture - they are fixed to the spacers and sole plate on site, once these have been positioned and



fixed to the foundations. This introduces an unwarranted on-site operation.

A far better alternative is to have completely pre-manufactured 'closure' panels. Instead of having individual spacers, a second 'sole plate' should be introduced. This sole plate is pre-cut to the required lengths and some are angle-cut along their length to accommodate the 3° incline. Each length is pre-drilled to take hookbolts. The pre-cut FRC panels are screwed to the sole plate during manufacture with the timber running along the top edge of each panel as follows:

Figure 5.10 Manufactured 'Closure' Panels



NOTE: The necessity for special closure panels is a feature of the 3 $\mu$  alternate design which is often criticised. Chapter 6 explores other geodesic designs and it is concluded (p.175) that the design of DOME B is preferred to that of DOME A, exclusively because no special panels are required around the base of the dome.

#### 5.4.2.2 'Window' Panels

Of the six pentagonal openings defined by the 'standard shell' of Dome A, four are used to accommodate windows. Various 'window-set' designs are possible (see Working Drawings Nos. 8, 9 and 10).

Dormer window designs allow a standard Woodlyte N43FX frame to be fixed vertically between special window panels. However it may be noticed from the photographs that one window of prototype Dome A was constructed of five triangular fixed panes of glass to suit the curvature of the dome. The dormers have an opening casement and a fanlight thus providing ventilation within the dome when necessary. The fixed triangular panes of glass, although providing a large amount of natural lighting within the dome, inherently provide no ventilation - the design of a triangular opening casement, at an acute angle with respect to the floor, introduces tricky waterproofing problems.

Prototype Dome A was constructed on site with special window panels custom-fitted around the frame - thus the timber framework of each 'window-set' was constructed first and subsequently covered with FRC cladding panels. It is suggested that the complete 'window-set' should be framed and skinned during the process of manufacture and installed on site as a completely pre-made unit by simply bolting the 'set' onto surrounding 'standard shell' panels. Thus on-site erection is simplified to the utmost with all waterproofing details along jambs, head and sill being taken care of in the factory, thereby obviating the need for tricky and time-consuming on-site operations. The on-site installation of alternative dormer window-sets does therefore not vary - only the manufacture is according to various designs and details.



5.15 Pentagonal opening ready for windows



5.16 'A modern indhlu'





5.17 Window-set No. 3



5.18 Window-set No. 4





5.19 Window-set No. 3



5.20 Ditto



5.19 Window-set No. 3



5.20 Ditto





5.21 Window-set No. 4



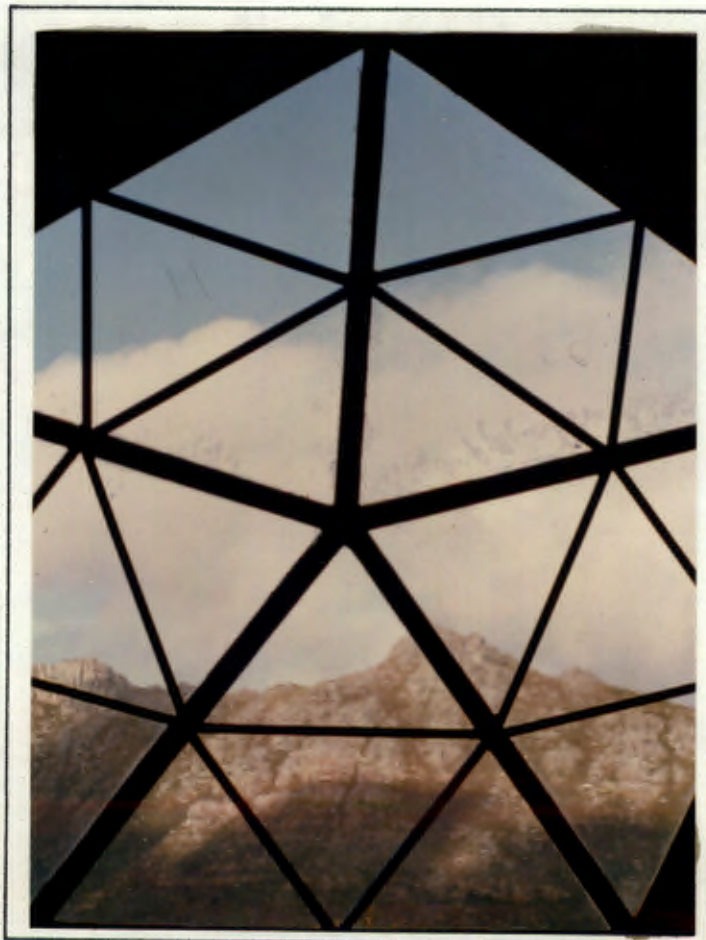
5.22 Ditto



5.23 Special picture window



5.24 Ditto

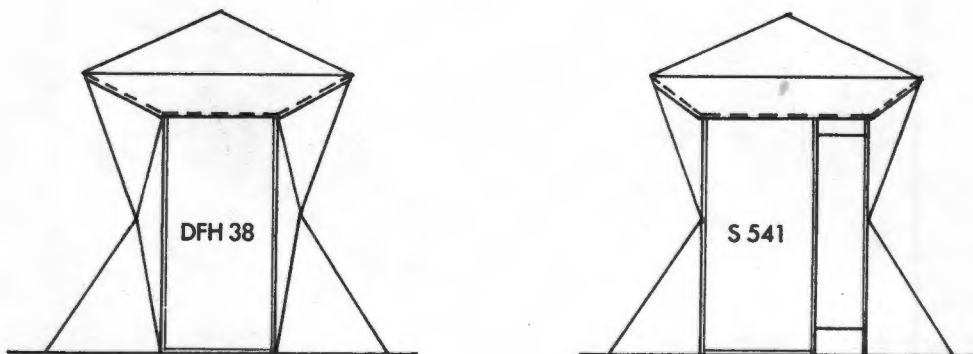




### 5.4.2.3 'Door' Panels

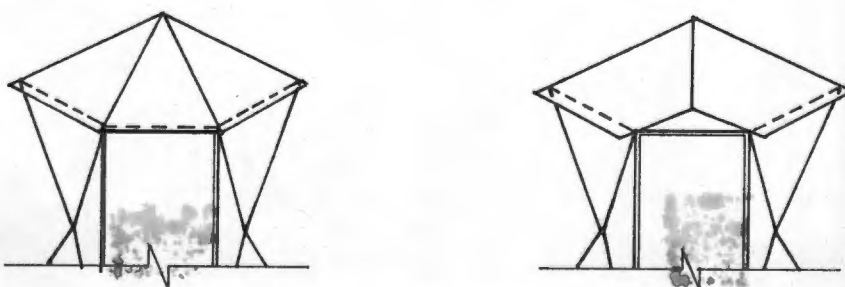
The manufactured 'door set' consists of a standard 'Woodlyte DFH 38' timber frame, as was used in the original prototype of Dome A, or a standard 'Woodlyte S541' frame, used in the reconstructed prototype. The frame is set between surrounding special door panels during the process of manufacture - thus waterproofing details are again executed in the factory (see Working Drawing No. 11).

Figure 5.11 Alternative 'Door-sets'



On site the 'door-set' is simply bolted onto surrounding 'standard shell' panels. A sloping hood, which projects beyond the frame, creating a small eaves to shed rainwater, is fixed over the top of the door. In order to avoid water running off onto people entering through the door, an alternative hood which sheds rainwater to the sides may be preferable.

Figure 5.12 Alternative Hood-Panels over Door



5.25 Door-set



5.26 Ditto



#### 5.4.2.4 Ventilation Panels

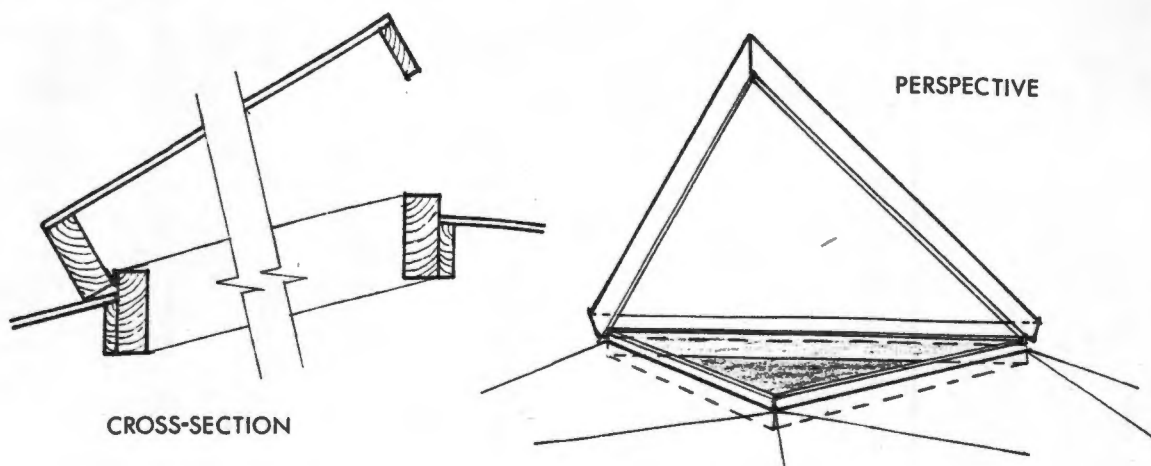
The pentagonal opening at the apex of the dome is utilised to provide ventilation within the dome. Various ventilation systems are possible (see Working Drawing No. 12) of which the simplest method is to fit five equal triangular panels into the opening and to fix a 100 mm-diameter FRC pipe into one of the panels. The vent-flue projects approximately 100 mm below the panel and 600 mm above the panel. A Bidim U-14 bandage is used as a flashing around the flue where it passes through the panel - the bandage is applied with rubberised bitumen (see 5.4.3). A commercially available rotating 'cowl' may be placed over the flue to avoid the possibility of water entering the dome through the vent-pipe.

Various alternative ventilation systems may be used, of which the following two seem to be most feasible:

- An 'umbrella' ventilation hood, consisting of five identical triangular panels, is projected vertically beyond the dome surface by means of five 200 mm high rectangular ventilation panels. These panels are perforated to allow hot air to escape, thus avoiding the stratification of air at the apex and the possibility of condensation at this point. The triangular hood panels project 200 mm beyond the vertical ventilation panels to create an eaves which sheds rainwater. A wire gauze screen should be attached to the inside of the perforated ventilation panels, similar to the conventional external air brick. A more sophisticated ventilation system is to have vertical louvres instead of perforated panels - this offers the additional facility of being able to close off the ventilation system when it is not required.

- One triangular panel at the apex may be hinged.

Figure 5.13 Hinged Ventilation Panel



In order to stimulate the circulation of air within the dome when all windows are closed, ventilation openings should ideally also be provided around the base of the structure - this may be achieved by means of vertical louvres. The warmer the weather the more ventilation is required to keep temperatures within the dome tolerable. By painting the dome white outside and by shading windows and facades that get north sunlight, the heat gain inside the dome is further reduced (see 7.1.1).

The ventilation hood, as described, is opaque - however a translucent hood has the additional advantage of illuminating the interior of the dome extremely efficiently (see 7.1.3). Alternatively the hood could incorporate solar heating - the inherent nature of manufactured panel construction, which lies at the heart of the design of Dome A, lends itself to solar heating.

#### 5.4.3. Sealing the Dome

When the complete dome has been erected the structure is waterproofed along joints between adjacent panels. The sealing of a dome is the major relatively skilled on-site operation (besides the foundation construction) and must be carried out either by a specialist or by a semi-skilled operative under close supervision. In order to transmit to an uneducated workforce the basic skill employed in sealing the external panel joints against the weather, basic training courses must be instituted (see 7.3.2.).



The concept of geodesic construction is relatively very novel: the art of geodesic has been practiced for many centuries, but the scientific corroboration was discovered only 35 years ago. As such it is inevitable that 'uniquely different operations to those generally found in conventional building practice' are only uniquely different because very few people have tried to perform them. It is certainly easier to assemble a geodesic dome than it is to construct a conventional house; also, it is easier to seal the external panel joints of a dome than it is to plaster a brick wall - the application of a 'Bidim' U-14<sup>⊗</sup> bandage with rubberised bitumen is not a difficult task once a person understands the basic application procedure:

- Prime panel joints 200 mm both sides of joint with 'Visaseal' rubberised bitumen, diluted in equal proportions with water.
- Apply a 200 mm wide 'Bidim' bandage over primed surface. The 'Bidim' will stick to the bitumen on the panels, because the water from the priming coat is quickly absorbed by the FRC and the remaining bitumen becomes tacky. However the bitumen must not be allowed to dry and lose its tackiness before the bandage is applied - if dry, re-prime!
- Apply with a brush the first coat of rubberised bitumen diluted with water (3:1), ensuring that the bitumen soaks through the 'Bidim'. When the bitumen emerges from the back of the 'Bidim', it makes contact with the tacky primed surface and bonds with it. It is of utmost importance to ensure that the 'Bidim' bandage is entirely saturated with bitumen before the first coat is allowed to dry.
- Apply a second coat of bitumen/water (10:1) as above.
- Apply final coat of undiluted bitumen.
- The entire dome surface is then painted with three coats of acrylic paint, diluted as above (see Working Drawing No.6)

For alternative methods of sealing and finishing the external surface of the dome see 4.2.1.3.

⊗ a non-woven, continuous filament needle-punched polyester geofabric



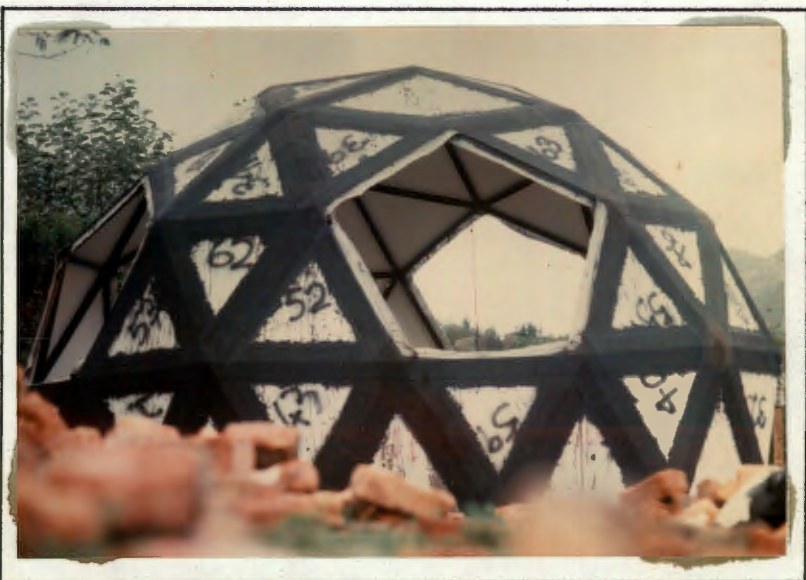
5.27 Joint between adjacent panels



5.28 Sealing joints with 'Bidim' U-14 and bitumen



5.29 Sealed 'standard shell'





5.30 The finished dome : Window-set No. 4



5.31 Ditto ..... and Door-set



5.32 Window-set No.1 and Special picture window





5.33 Finished Window-set No. 1



5.34 Special Window



5.35 Window-set No. 4



5.36 Ditto





## CHAPTER SIX

## 6. ALTERNATIVE GEODESIC DESIGNS

6.1 Dome B: 3-frequency Geodesic, 5/8-sphere, icoso-alternate 'truncatable' breakdown, vertex-zenith

David Kruschke, in his book 'Dome Cookbook of Geodesic Geometry', derives chord factors for a 3-frequency alternate breakdown which are in much closer agreement with Fuller's breakdown than the more conventional alternate breakdown, the details of which are published in 'Domebook 2'. The 'truncatable' alternate breakdown defines perfectly horizontal great circle lines at both the 3/8- and 5/8-sphere cut-off planes, thus allowing the dome to sit flat on its base along every edge of truncation, obviating the need for cutting triangles.

Having experienced the construction problems involved in dealing with uneven cut-off lines of the alternate breakdown, it is undoubtedly realised that the 'truncatable' alternate is a much neater, simpler and architecturally a much 'purer' design. It is thus suggested that the latter breakdown should supersede its more conventional counterpart.

The major drawback is that the 'truncatable' alternate design results in two 'standard' triangles (the third triangle is used for various openings as in Dome A), as compared to the single 'standard' triangle required for the



conventional alternative breakdown. Besides the obvious disadvantages of manufacture and erection, the extension of the dome by 'nesting' another one onto it, becomes more difficult.

## 6.2 Dome C: 4-frequency geodesic, $\frac{1}{2}$ -sphere, icosatriacon breakdown, edge-zenith

It has been suggested that the purist dome builder prefers the triacon to the alternate breakdown (see Appendix B.6.4). The edge-zenith orientation of the icosahedron defines a complete great circle line at the dome's equator; thus for ease of truncation, this orientation in space is the optional choice.

A 4-frequency triacon dome has relatively smaller triangular faces than the 3-frequency alternate dome. Since the maximum possible size of a dome is usually limited by the standard dimensions of cladding panels, a 4-frequency triacon dome can be increased to a maximum diameter of 8,7 m by using standard cladding panels made of plywood or FRC. The resultant dome covers a floor area of 60 m<sup>2</sup>, almost twice the area enclosed by a 3-frequency alternate dome designed within the parameters of standard cladding panels available. In relative terms, the 4-frequency triacon dome is thus a more economical method of dome construction. It is suggested that a dome which is required to enclose a floor area of more than 35 m<sup>2</sup> and less than 60 m<sup>2</sup> should be designed according to a 4-frequency triacon breakdown.

The 4-frequency triacon breakdown results in three different 'standard' panel sizes, although two of these are similar, the one being a 'left' triangle, the other a 'right'.

### 6.3 Dome D: 4-frequency geodesic, $\frac{1}{2}$ -sphere, octa-alternate breakdown, vertex-zenith

The icosahedron is not the only polyhedron from which geodesic domes can be derived. The tetrahedron and octahedron are both omnitriangulated platonic polyhedra (see Appendix B) and can therefore serve as the basic figure from which the geodesic dome is derived.

From a discussion between Lloyd Khan and Bill Woods:

"Lloyd: Well, the octahedron turns out to be better than the icosahedron which we used.

Bill: Yeah. The icosahedron is no good for domes . . .

Lloyd: We used the icosahedron because of aesthetics.

Bill: Yeah. Well the point I'm getting at is I'm strictly a man of mechanics. Make it work the best that it will . . ." (1)

Fuller was a purist, deriving the best advantage from a situation by applying the optimal, most logical solution. The icosahedron is a triangulated platonic polyhedron which most closely approximates a sphere - it is derived from the vector equilibrium, an isotropic vector matrix, and theoretically seems to be the optimal volume-enclosing structural system upon which to base practical designs of structure. Consequently, Fuller derived his geodesic dome designs by analysing ico-sa-based structural systems (see Appendix B).

However there are practical advantages in octa-based geodesic dome designs. Probably the most pertinent fort   is that at any vertex of the octahedron four edges meet at 90   to each other, whereas the icosahedron has five edges meeting each other at an angle of 72  . In today's 'square' society, a 90   angle is bliss - the octa-alternate dome can be joined onto

any structure manifesting  $90^\circ$ ,  $180^\circ$  or  $270^\circ$  surface angles (see 7.2.3: Figure 7.9 ). In addition, there is always a perfect natural hemispheric truncation in both the triacon and alternate breakdowns.

4-frequency geodesic,  $\frac{1}{2}$ -sphere, octa-alternate breakdown, vertex-zenith



The triangular faces of the frequency-modulated octa-based geodesic dome vary in size much more than in its icosahedron-based counterpart. The longest 3-frequency octa-based edge-length is 25 per cent longer than the longest 3-frequency icosahedron-dome edge-length for structures of similar radius. Thus in order to enclose a reasonable floor area and still use standard size sheet panel cladding elements, some triangles of the octa-based dome must be covered by 'patching' panels with two separate pieces of sheet cladding.

#### 6.4 Dome E: Triacanthedral Zome

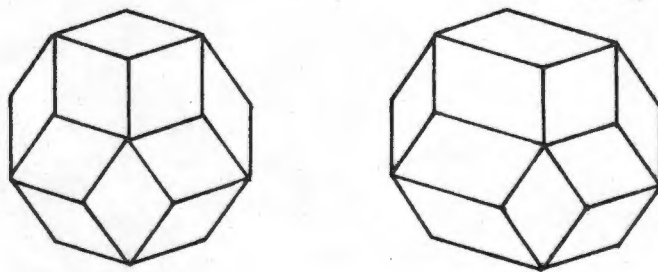
'Zomes' are structures based on 'zonahedra' and were named, developed and patented by Steve Baer.

"It (the geodesic dome) is complicated in structure and simple in shape. Zomes are simple in structure and complicated in shape." (2)

The greatest limiting factor of domes is their inflexibility in shape. They are always circular in plan and symmetrically or asymmetrically spherical

in form - any variation would destroy the structural properties of the geodesic dome. Zonahedra are convex 'solids' in which the opposite edges of the faces making up the structure are equal in length and parallel to each other. These edges encircle the structure forming bands of parallel edges called 'zones'. A zone can be symmetrically expanded or contracted along any 'zone' of parallel edges without changing any other part of the polyhedron or distorting any of the angles, although the floor becomes oval.

Figure 6.1 Triacontahedron expanded along a 'zone' of parallel edges

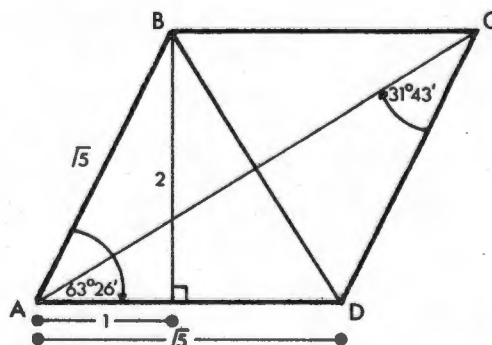


The rhombic triacontahedron is a zonahedral structure with thirty diamond-shaped faces defining six 'zones' of parallel edges. It forms the basis of the 'triacon' geodesic breakdown (see Appendix B.6). Each face of the triacontahedron manifests the following critical constant dimensions:

Figure 6.2 Diamond face of Triacontahedron

$$\frac{AC}{AB} = 1,7010$$

$$\frac{BD}{AB} = 1,0515$$



AC is not part of the triacon breakdown - it defines an imaginary icosa-

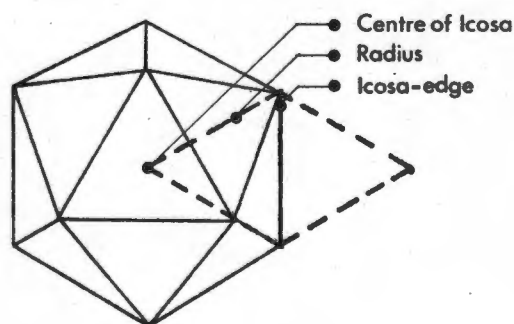


edge. BD defines a dodeca-edge, which divides the diamond-shaped face of the triacontahedron into two similar triangles, resulting in a 2-frequency 'triacon' breakdown.

Each diamond face is symmetrically bisected along its short diagonal by an edge of the dodeca and along its long diagonal by an icos-edge, thus defining four LCD right-angled triangles of the icosahedron.

The dodeca-edge (BD) to triaconta-edge (AB) ratio is 1,0515. Similarly, the edge to radius ratio of the icosahedron is 1,0515 (see Appendix B.5.2). This means that each diamond face of the triaconta is in direct proportion to a 'golden diamond' of the icos, which relates the icos-edge lengths to the radius of the polyhedron.

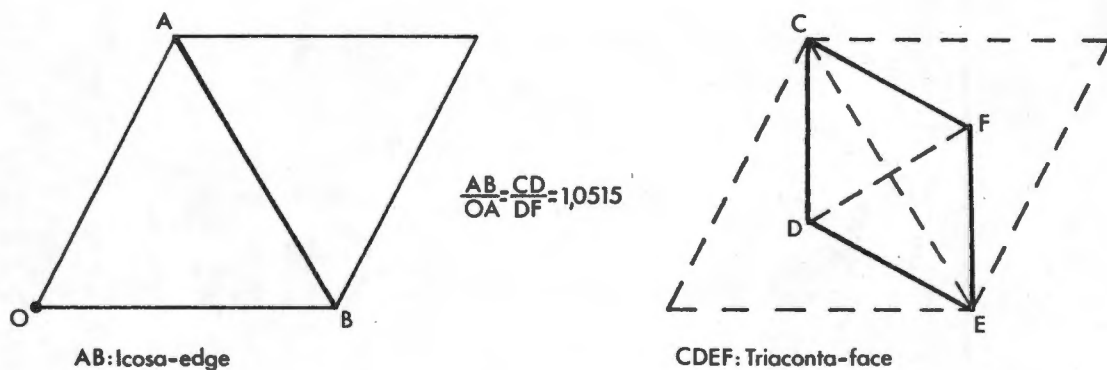
Figure 6.3 'Golden Diamond' of the Icosahedron



The angles of a diamond face of the triacontahedron are identical to the angles of a 'golden diamond' of the icosahedron. However the edge-length is symmetrically shortened for a triaconta of equal radius to an icos, because the icos-edge defining the short diagonal of a 'golden diamond' is longer than the dodeca-edge defining the short diagonal of the triaconta diamond, for polyhedra of equal radius. It is interesting to note that the long diagonal of the triaconta diamond defines an icos-edge - thus the two polyhedra are inherently of equal radius.



Figure 6.4 Relationship between 'Golden Diamond' of the Icosahedron and Diamond Face of the Triacontahedron



A detailed analysis of zones is beyond the scope of this study, as it involves fairly extensive mathematics and some extremely complicated polyhedral geometry, defining the 'recursive growth' of zonahedral 'stars'. It suffices to note that there are two major practical advantages in zones as compared to domes:

- Their flexibility of shape allows for simple and very interesting extensions and symmetrical distortions of the basic zonahedral forms.
- They are 'nestable' and are thus easily fused to form 'clusters'.  
(see 7.2.3)

## Chapter 6 : References

- 1 Kahn, L., Shelter, Shelter publications, California, 1973, p.121.
- 2 Baer, S., Zome Primer, Zomeworks, New Mexico, 1970, p.2.

## CHAPTER SEVEN

### 1. EVALUATION OF PROTO-TYPE DOME A

#### 7.1 Environmental Performance

##### 7.1.1 Thermal Performance

"The indoor environment in any unconditioned building is a product of the prevailing outdoor climate and the way in which the building itself modifies the climate, the latter being known as the thermal performance of the building." (1)

##### 7.1.1.1 Introduction: Thermal Comfort

Thermal performance is measured by the effectiveness of the design, layout and materials of a building in providing an indoor environment which is thermally comfortable with little or no energy-consuming artificial aids. In designing for naturally induced thermal comfort inside buildings, the prevailing locational climatic conditions must be established and a thorough understanding of the physical principles of heat mechanics is essential.

The combined effects on an indoor thermal environment of all factors affecting thermal comfort are extremely difficult to establish in absolute qualitative terms. Varying human sensations of personal comfort levels (the set of thermal conditions which feels most comfortable) makes it

impossible to satisfy everyone. The degree of activity, the rate of individual metabolisms and the type of clothing, all determine personal comfort needs. The aim in building design is to satisfy the majority and to minimise the degree of dissatisfaction of the rest, by providing the maximum opportunities to allow individuals to satisfy their own comfort needs. Thus buildings should be designed to take an extensive passive role - and, if necessary, equipped to take an active role - in creating indoor thermal comfort.

A thermal environment is determined by many variable and interdependent factors which operate simultaneously. In the natural environment, the major factors are air temperature, humidity, air movement and radiation. A designer must take due cognisance of these factors in conjunction with the thermal properties of building materials, systems and shapes, in order to produce naturally induced thermal comfort inside buildings, at least in quantitative terms. At present computer simulation procedures to establish the thermal performance of buildings in quantitative terms are being corroborated by experimentation. However in the absence of computer data, various empirical procedures, such as the CR method recently developed by the NBRI, are being extensively applied by designers. In applying the CR method it is assumed that direct sun penetration in summer has been controlled and that provision has been made for adequate cross-ventilation. The method is based on an experimentally verified correlation between:

- the amplitude ratio, expressing the relationship between indoor and outdoor temperature, and
- the product of the active thermal capacity of the structure (C) and the weighted resistance to heat flow of the outer shell (R).

### 7.1.1.2 Heat mechanics, thermal properties of materials and thermal performance of buildings

In order to evaluate the thermal performance of buildings one must recall the elementary study of heat mechanics which involves the transfer of heat from one body to another. Heat transfer always occurs from a warmer object to a colder one, resulting in heat loss and heat gain respectively. There are three basic mechanisms of heat transfer:

- Radiation
- Conduction
- Convection

The control of an indoor thermal environment depends largely on the heat gain or heat loss through the envelope of the building. Thus the thermal performance of the building is determined by the degree to which the various mechanisms of heat transfer are passively controlled.

#### 7.1.1.2.1 Radiation, solar exposure and fenestration

Infra-red electromagnetic radiation occurs either as shortwave solar radiation or as longwave terrestrial radiation. Radiant heat is exchanged between objects which can 'see' each other and have different temperatures. As the difference in temperature grows, the radiant heat flow increases at an increasingly rapid rate. However as soon as an opaque object is placed between the two heat-exchanging objects, the exchange stops immediately.

Radiant heat is either reflected, absorbed or emitted by a body. The degree of reflectance, absorptance or emittance depends largely on the colour and texture of the surface, and on whether heat is radiated directly



from the sun or from terrestrial sources, such as sun-warmed objects, fires, plants or the human body.

**Table 7.1** Effect of Radiant Heat on Various Surfaces

| Type of Surface   | Solar Radiation          |             | Terrestrial Radiation    |             |
|-------------------|--------------------------|-------------|--------------------------|-------------|
|                   | Absorptance<br>Emittance | Reflectance | Absorptance<br>Emittance | Reflectance |
| Bright Aluminium  | ,05                      | ,95         | ,05                      | ,95         |
| Galvanised Steel  | ,25                      | ,75         | ,25                      | ,75         |
| White Paint       | ,20                      | ,80         | ,90                      | ,10         |
| Fresh Whitewash   | ,12                      | ,88         | ,90                      | ,10         |
| Light Green Paint | ,40                      | ,60         | ,90                      | ,10         |
| Dark Green Paint  | ,70                      | ,30         | ,90                      | ,10         |
| Black Paint       | ,85                      | ,15         | ,90                      | ,10         |
| Concrete          | ,60                      | ,40         | ,90                      | ,10         |

Source: Allen, E., How Buildings Work: The Natural Order of Architecture, Oxford University press, New York, 1980, p. 51.

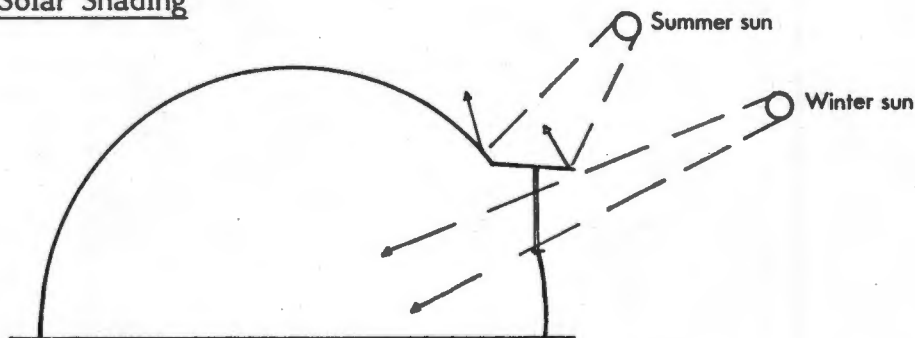
A pertinent fact to note is that bright metallic surfaces reflect both solar and terrestrial radiation to a large extent, whereas white painted surfaces reflect very little terrestrial radiation. Thus bright metallic foils may be used as thermal insulators (see 7.1.1.2.2), but only if they are placed adjacent to an airspace, so that heat conduction does not occur through the metal.

Solar radiation, being at a much higher temperature than terrestrial radiation, must be carefully controlled to avoid excessive heat gain inside buildings during the summer, by using bright or light-coloured external surfaces. In addition, the degree of solar exposure and fenestration can be controlled by careful design. All sun control measures must take into

account both the diurnal motion - and the apparent seasonal migration - of the sun. Most sun penetration problems merit a detailed investigation in their own context - however there are some general design recommendations:

- During summer it is relatively easy to shade a north wall with a modest roof overhang or a horizontal ledge, which will nevertheless leave it exposed to the lower sun in winter. Thus the major facades of buildings, and especially the principal window areas, should be orientated to the north, or at least to within about  $20^\circ$  of north.

Figure 7.1 Solar Shading



- In the event of an insufficient roof overhang, the walls must be painted white to reflect most solar radiation impinging on them. In addition, north-facing windows must be shaded on the outside with shutters, louvres or awnings to prevent excessive heat gain in summer. Alternatively deciduous trees may be grown on the north side of the building, to provide shade in summer, shedding their leaves in late autumn to allow the winter sun into the structure.
- East and west facades are exposed to direct radiation from a near perpendicular direction and are more difficult to shield. They should therefore be kept to a minimum and include little or no window area.

#### 7.1.1.2.2 Conduction, insulation and heat capacity

The resistance of a material to the conduction of heat is a measure of its insulating value. The rate of heat gain or heat loss through any portion of a building envelope is directly proportional to the difference in air temperature between the interior and exterior (amplitude ratio) and to the overall thermal transmittance or 'U-value' - or inversely proportional to the overall thermal resistance - of that portion of the building. In colder countries thermal insulation tends to be the first line of defence in energy conservation in buildings. In warmer climates it has a more subsidiary role to play, since the mass or heat capacity of the building enclosure takes on the major priority. It is important to note that high heat capacity elements of a building enclosure should not be insulated from the inside - the practice of providing insulative floor coverings, such as carpets or parquet, greatly reduces the often cardinal role played by a concrete floor in temperature stabilisation, particularly in a single storey building of relatively low mass.

Good thermal insulating materials are characterised by low heat capacity. Air, which is prevented from circulating, is an extremely efficient insulator, whereas water and dense metals are good thermal conductors. Insulation is usually sandwiched between other layers of the construction with the intention of reducing the rate of heat flow through the sandwich.

In designing an effective insulation system great care must be taken that framing members do not create thermal bridges - thus timber frames should be used in preference to metal. Glass has a notoriously low resistance to the flow of heat; however by double glazing, air is trapped between the two sheets of glass and the thermal resistance of the glazing system is vastly increased. However if the air is allowed to circulate,

convective flow of heat will occur (see 7.1.1.2.3). Most insulating materials, such as fibreglass, rockwool, foamed polyurethanes, etc. consist of a matrix of inert, low thermal conductivity material which serves to prevent convective motion of the entrapped air which is the principal insulator. Insulating materials must be kept dry because water, displacing the air from the matrix, greatly reduces their insulating value (see 7.1.2).

In hot, dry climates, with relatively large daily temperature differentials, a building envelope constructed of a thick layer of high heat capacity material, such as brick, concrete, stone or adobe, offers distinct advantages in the control and stabilisation of an indoor thermal environment. Heat is stored in layers within the thickness of the wall or roof and it is transmitted slowly from the warmer to the colder surface. When a straight-line temperature gradient is reached, the colder side of the wall or roof approaches a temperature equal to the air temperature on that side, and the warmer side is at a temperature approaching the warm-side air temperature. Until this stable condition occurs, the wall or roof will transmit heat at a rate slower than would be predicted solely from the thermal resistance (or insulating value) of the element. Once the stable condition is achieved however, heat transmission will occur at the predicted rate, which for high heat capacity materials is relatively rapid. The thickness of the building envelope can be varied to suit local cyclic temperature differentials, the aim being to dampen and delay air temperature fluctuations inside buildings to the optimal extent.

In warm desert climates or even in temperate climates, the daytime outdoor air is hot and heat flows slowly through a building envelope of relatively great heat capacity towards the interior. Before excessive heat gain occurs inside the building, the sun sets, the outside air temperature drops and the heat stored within the building envelope slowly flows back

towards the cool exterior. In doing so, the envelope acts as a buffer against heat being drawn from the interior during the night, thus keeping the interior warmer than its surroundings.

In hot, damp climates where night temperatures remain high, building enclosures should have a low heat capacity, so that they react relatively quickly to cooling breezes and small decreases in air temperature. Ventilation systems are often necessary to maintain a comfortable indoor air temperature and to control the humidity inside the building. In addition, external surfaces should be designed to reflect as much solar heat as possible.

#### 7.1.1.2.3 Air movement, convection and ventilation

Unless the prevailing air temperature is very high, air movement generally has the effect of cooling people by promoting conductive, convective and evaporative heat transfer from the skin. Thus it is often more economical to provide natural fresh air flow through a building or to stir the atmospheric contents of a building, rather than to provide an equivalent amount of air cooling. Air movement, whether induced naturally or artificially, is used not only to control the temperature and humidity of the air inside buildings, but also to remove odours and noise.

Natural ventilation through a building may be induced by one or both of two motive forces: wind and convection. Wind forces usually predominate over thermal forces, but both result in a flow of air from a high-pressure zone to a low-pressure zone. As wind passes over and around a building, high- and low-pressure zones are induced by the building shape. In designing for natural ventilation, air inlets and outlets should be provided respectively at points of high- and low-pressure created by prevailing



winds. Pressure differentials causing convective ventilation are created by the difference in density between warmer and cooler air - being weaker than wind forces, relatively large ventilation openings are necessary.

Most designs for natural ventilation of buildings use windows to control the volume, velocity and direction of airflow. In addition, roof ventilators, as used in Dome A, are extremely useful in supplementing natural air movement within buildings.

In hot climates it is usually desirable to allow wind-powered and convective air movement to operate simultaneously in lightweight buildings which would otherwise heat up excessively due to the relatively low thermal capacity and thermal resistance of lightweight envelopes; the heat generation inside the building from sun-warmed objects and various human activities such as cooking, bathing and breathing, also increase heat gain. In cold winter conditions high rates of natural ventilation are not desirable, as this would cause excessive heat loss from within buildings.

Heat losses due to the convective transfer of heat across surfaces are computed on the basis of maximum prevailing wind velocities; thus wind-sheltered buildings inherently require less heating fuel. Further energy-savings derived from sheltering buildings from the wind ensue from an undisturbed insulating surface film of air which is held against the outside surface by friction - high winds largely destroy these exterior films. In addition wind-driven precipitation is prevented from striking the building, thus eliminating a possible source of moisture penetration through the shell of the building (see 7.1.2).

Convective air circulation patterns inside a building depend on prevailing climatic conditions and on the thermal properties and performance of the

building envelope. Convective cooling of internal air by a relatively cold envelope increases the density of the air near the inner surface and causes it to sink to the floor, cooling further as it sinks. Warmer air rises in the centre of the enclosure to replace the cooler air and in turn is cooled by the envelope. This convective flow of heat reverses direction when the building envelope warms up sufficiently to cause heating of internal air near the perimeter - the heated air rises to be replaced by cooler air sinking near the centre of the building and which is then also heated, thus continuing the convective flow pattern. Similarly, sun-warmed surfaces heat up the adjacent air, resulting in new patterns of convective air circulation. Wind-powered air movement through a structure and fan-stirred local atmospheric movement within a building both affect natural convective flow patterns.

#### 7.1.1.2.4 Relative humidity and condensation

Relative humidity is represented by a percentage figure which defines the quantity of water vapour the air contains relative to the maximum quantity of vapour it could potentially contain at a given temperature. The relative humidity may be decreased by increasing the air temperature. When the temperature drops to a point where relative humidity just reaches 100 per cent, this temperature is called the 'dew point' of the air. If cooling continues below the dew point, the superfluous water vapour condenses as fog, as for example on window panes in cold weather. The most serious condensation problems occur when an insulated assembly is placed between warm relatively humid air on one side and cool relatively dry air on the other side. Thus in winter, a heated internal environment filled with water vapour from breathing, bathing and cooking is prone to condensation, especially in winter rainfall areas, as is a cooled,

de-humidified building in a hot, humid climate.

The higher the moisture content of the air, the greater is the vapour pressure which drives water vapour into areas of lower vapour pressure. If moist, warm air is on one side of a wall and drier, cool air on the other, water vapour migrates through the wall from the moist side to the dry side. Some vapour pressure loss from the moist side to the dry side is evident and is reflected in a progressive decrease in the dew point temperature as the vapour moves through the wall. In addition, the temperature within the wall drops gradually from the warmer surface to the cooler one through various layers of construction, at a rate depending on the thermal resistance of the layers. If at any point within the wall the temperature falls below the dew point the excessive water vapour condenses and a slight local decrease in vapour pressure of the air is created - thus vapour from surrounding high-pressure areas will migrate towards the area of condensation until the pressure or temperature differential decreases sufficiently to stop the condensation. In order to ensure that any insulating material within the wall does not become damp, a vapour barrier (a continuous plastic or metal foil sheet) should be placed between the insulating layer and the warm side, as near as possible to the latter. In addition, adequate ventilation on the cool side will help clear moisture from that surface.

#### 7.1.1.3 Thermal Performance of Dome A

"Energy experts will tell you that the first important factor affecting energy consumption is a building's shape, not the insulation or the heating system. A dome exposes 30 per cent less surface area through which heated or cooled air can escape." (2)

The volume to surface area ratio of a sphere exceeds that of any other

volume-enclosing form. The heat loss and heat gain are thus both minimised for a given shell construction and given temperature differentials between exterior and interior, because there is the least surface area per unit of volume through which the loss or gain can occur.

#### 7.1.1.3.1. Conduction

The geodesic dome, being a lightweight structure, has the major drawback of a very low heat storage capacity within the shell. The rapid transfer of heat through the shell may be greatly reduced by the addition of a layer of foil-backed insulation into the shell sandwich, positioned adjacent to a generous air space just below the external cladding, thereby preventing excessive heat loss in winter, as well as solar heat gain in summer.

#### 7.1.1.3.2. Radiation

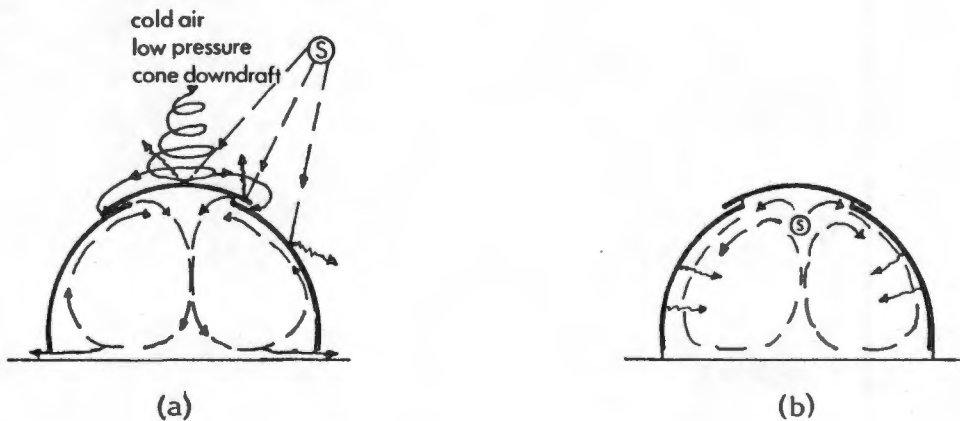
In hot weather solar radiation impinging on the convex external surface of the shell is reflected and diffused, especially from a bright metallic surface or from a white surface such as the finished exterior surface of Dome A. Solar shading by means of deciduous trees and projecting hoods over windows will further reduce heat gain inside the dome, as will a metal foil positioned adjacent to an air-space within the shell sandwich (as explained above).

In cold weather some long-wave thermal radiation emitted from inside the dome by sun-warmed objects, by the human body and by artificial heat sources, is reflected by the concave interior surface towards the volumetric centre of the structure - thus a centrally-located source of heat

inside the dome is extremely efficient in heating the interior. The best position for the heat source is on the central axis, a meter or so (depending on the size of the dome) below the apex, producing the optimal convective interior air circulation pattern, while keeping the floor area clear (see figure 7.2.).

#### 7.1.1.3.3 Convection

Figure 7.2 Interior Atmospheric Motion



Summer: Interior Motion is an Involuting Torus

Winter: Interior Motion is an Evolving Torus

Air moves naturally in circular patterns, with hot air rising and cooler air sinking. The spherical shape enhances these natural air circulation patterns within a dome, thus simplifying the process of convective heating and cooling - however for the same reason noises, odours and fires circulate easily. To stimulate air circulation and to prevent the stratification of warm, relatively humid air against the cooler interior surface of the dome at the apex - and thus to prevent the possibility of condensation - there should be ventilation openings around the base of the structure and at the apex. To control air movement, the vents should be louvred or designed in some other way so that during cold weather the warm air inside the dome is prevented from escaping.



#### 7.1.1.3.4. Condensation

Condensation within the insulated stressed skin shell of a building such as Dome A has been cited as a major cause of moisture accumulation and consequent poor thermal performance (see 7.1.1.2.4.). A metal foil sheet backing to the insulation acts as a vapour barrier and is placed between the internal lining and the insulation where relatively moist, warm air is prevalent. The cool side within the shell, the inside surface of the external cladding, is prone to vapour condensation and should be adequately ventilated to help clear moisture from the surface. In order to promote air circulation it is suggested that struts of stressed skin panels are drilled at frequent intervals along their length - these holes will encourage a convective flow pattern around the dome shell within the air gap, which is linked to the outside air by means of ventilation openings around the base of the dome and the apex. Alternatively panels may be sealed off, so that an insulating gap of unstirred air is created within the shell. The moisture content of the air remains constant and should be low enough to ensure that the lowest annual prevailing temperature does not allow the air to reach dew point.

#### 7.1.1.3.5. Solar Heating

The construction of lightweight panel domes inherently lends itself to the incorporation of solar heating panels. In America many technologists involved in geodesic dome design and construction have switched the emphasis of their research from structural design to environmental design, especially solar heating and other energy-efficient methods of providing autonomous houses. However a detailed analysis thereof is beyond the scope of this study, but it is undoubtedly a topic deserving extensive future research.

### 7.1.2. Moisture Exclusion

The need to eliminate water infiltration through a building envelope is self-evident.

Floors must be protected from ground-water and capillary moisture penetration - the most effective method of achieving this is to place a continuous sheet of plastic or other impervious membrane underneath the floor and to allow the sheet to continue up to at least 150 mm above natural ground level (see 5.2: Working Drawing No. 7).

The external surface of the stressed skin panel shell must prevent both the penetration of precipitation (especially wind-driven rain) and excessive water vapour - special care must be taken to protect the insulating layer from moisture invasion.

Thermal movement within the building shell, as well as tensile stress around the base, must be carefully considered in designing an impervious, durable external surface. The curved shape of the dome causes differential expansion and contraction as the sun strikes the surface at various angles throughout the day. The geodesic dome consists of many individual panels - thus movement which may occur along joints takes place simultaneously between a number of panels and occurs on a relatively small scale.

Various methods of sealing the dome against moisture migration through the external surface have already been analysed (see 4.2.1.3 and 5.1.4.3). Windows and doors have a sloping hood which projects beyond the opening to shed rainwater. Since rainwater runs over the entire surface of the dome and accumulates around the base of the structure, a rainwater channel should be provided to divert it, so as to avoid the undermining of the foundations.

### 7.1.3 Natural Illumination

Windows are not easily accommodated on a curved surface with triangular structural elements. The best solution is to introduce dormer windows which allow the use of standard windows, fixed vertically. Dome A has four identical window openings which are positioned so as to eliminate the icosacaps of the dome, as previously described - however a number of alternative designs are possible (see 5.1.4.2.2). Each standard N43FX Woodlyte window has a glazing area of almost one square meter. Triangular windows, which do not break the dome's geometric symmetry, are more complex unless used simply as picture windows with no opening sections - they provide much more natural light than dormer windows.

The orientation and size of windows must be carefully taken into account in designing for optimal natural illumination, as well as thermal performance (see 7.1.1.2.1), and natural ventilation (see 7.1.1.2.3). Three dimensional scaled models are invaluable aids to the designer.

Additional natural illumination may be provided by replacing the opaque ventilation hood at the apex of the dome with a translucent hood. Being a source of light from above, this form of illumination is extremely efficient, as light cascades down the interior surface and is reflected into the dome, especially from a white surface.

## 7.2. Structural Considerations

### 7.2.1. Integrity

"In terms of design, the dome is the strongest and most durable of architectural forms - a dome was the only structure to withstand the direct blast of the atomic bomb at Hiroshima." (3)

The triangle is the only inherently stable structural configuration - in combination with the sphere, which produces the greatest strength per unit of invested material, the triangular three-way geodesic grid results in a structural framework which has a higher strength to weight ratio than most conventional man-made land-based enclosures.

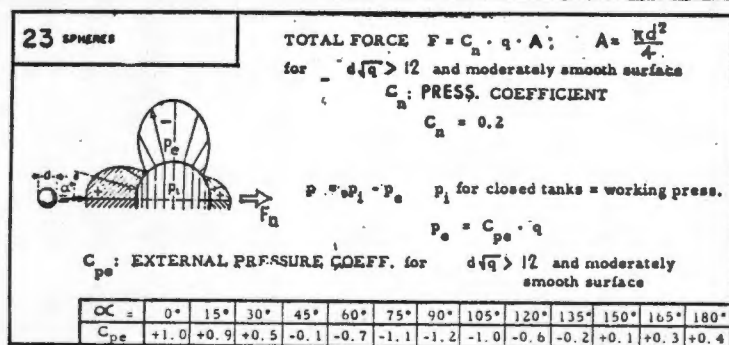
Stress analysis used in geodesic domes is unlike that of any conventional buildings. Geodesic structures are statically indeterminate and as such stresses can only be predicted with the aid of computer simulation models. 3-D scaled models also offer some insight into the forces acting within a geodesic framework and how these forces are distributed under static and dynamic stress conditions. Stresses within the basic structural geodesic framework are equilibrated along great circle chords. As the frequency of subdivision of the chords increases, the number of structural members increases proportionately, resulting in a progressively more spherical structure and in a greater distribution of stress and consequently in a stronger, more efficient structural configuration. However when a rigid skin is applied to the framework stresses are no longer equilibrated along great circle chords, but are localised in different areas of the skin, depending on the direction and magnitude of the loads (mainly wind and thermal forces).

The junction between the dome superstructure and the foundations is subjected to severe tensile stress. Firstly, the tendency towards tensile

spreading of the base members, due to the thrust exerted by the superstructure, is induced by the truncation of the dome into a partial sphere. Secondly, a considerable wind drag exerts itself on spherical structures. The high negative external pressure coefficient modifies lateral wind pressure and causes a severe upward drag in high wind conditions. Thus an 'edge beam' or 'ring beam' foundation is essential and the method of anchoring the superstructure to the foundations is critical to avoid structural failure at this point.

Figure 7.3. External Pressure Coefficient of Spheres

SDR 3, App. A



### 7.2.2 Ease and Speed of Construction

The major advantage of the lightweight geodesic panel dome is that the panels are light enough to be easily handled by one person and that the on-site assembly of the kit is extremely simple. The superstructure can be assembled and finished on a self-help basis, according to a detailed instruction manual, in four working days by a gang of two operatives and two labourers (or one family). Alternatively, if mass-produced by a specialist contractor, a gang of one foreman, six operatives and eight labourers can erect 100 dome superstructures in 103 working days - almost a dome a day. The construction of the foundations is not proposed as a self-help operation at this stage, although a 'foundation kit' of precast components could quite easily be manufactured for self-help on-site construction.



Another relatively skilled on-site operation is that of sealing the dome (see 5.4.3). However, under close supervision and with the aid of a graphically illustrated basic instruction manual, a semi-skilled person could quite easily undertake the task.

NOTE: Training and Supervision are inherent prerequisites to the introduction of uniquely different building ethic as employed in geodesic construction. (see 7.3.2)

The present and future scale of demand for low-income housing can clearly not be met by means of rationalised conventional heavyweight construction, whether mass-produced or constructed on a self-help basis. The reason for this is that conventional building methods involve some relatively skilled on-site operations as well as being characterised by an extremely low output rate of finished units. It is therefore proposed that under the present circumstances of demand, a lightweight industrialised kit building system should be considered as an alternative method of low-income house construction (see 2.3).

### 7.2.3 Natural Extensions or Additions

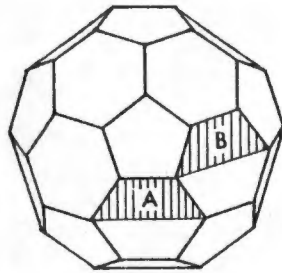
All geodesic domes, whatever size, frequency, method of breakdown or orientation in space, are nestable in one of several ways - by plane intersections, by passages or by perfect fusion. However each design must be considered individually - scaled models are invaluable and essential in establishing extension possibilities.

NOTE: For perfect fusion of two domes, they must have complementary 'fusion rings' with respect to the ground.

Dome A can be perfectly fused with another similar dome to produce a dwelling with an enclosed floor area of 70 m<sup>2</sup>.

With a vertex-zenith orientation, the truncated icosahedron (consisting of hexagonal and pentagonal facets - see Figure 5.7) has complementary half-hexagons at the  $3/8$ - and  $5/8$ -cut-off planes.

Figure 7.4 Complementary Half-hexagons of the Truncated Icosahedron



**NOTE:** Half-hexagon A forms an obtuse angle with the  $5/8$  cut-off plane. Half-hexagon B forms an acute angle with the  $3/8$  cut-off plane. The two angles are complementary - thus the two half-hexagons will fuse perfectly.

Each half-hexagon of the truncated icosahedron forms three triangular facets of the 3-frequency icsa-alternate dome, which means that the two sets of three triangles each (from half hexagons A and B) can be fused along the edges of each set. Note that the fusion ring is only 1,200 m above the cut-off plane - thus a hood is required to produce sufficient headroom.

Figure 7.5 Fusion Rings of 3-frequency Icosa-Alternate Breakdown Domes

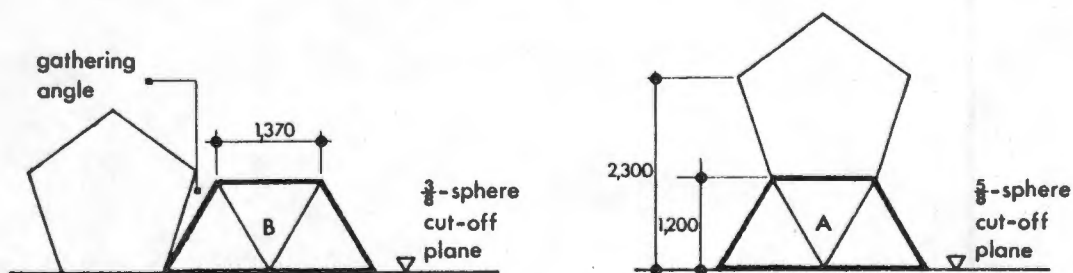
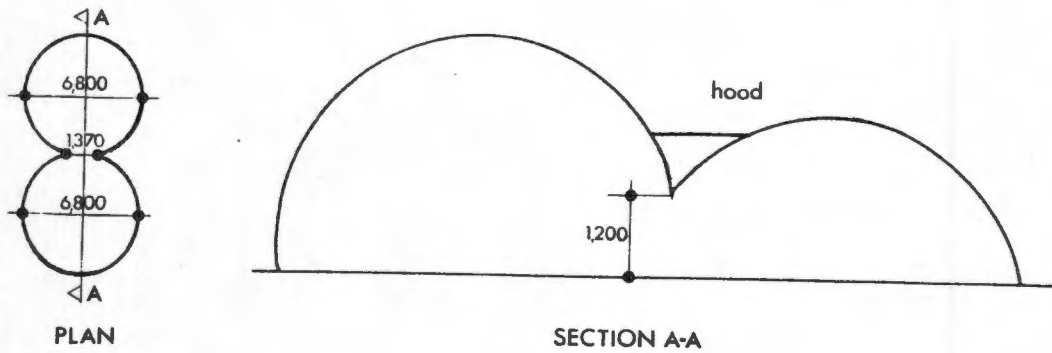
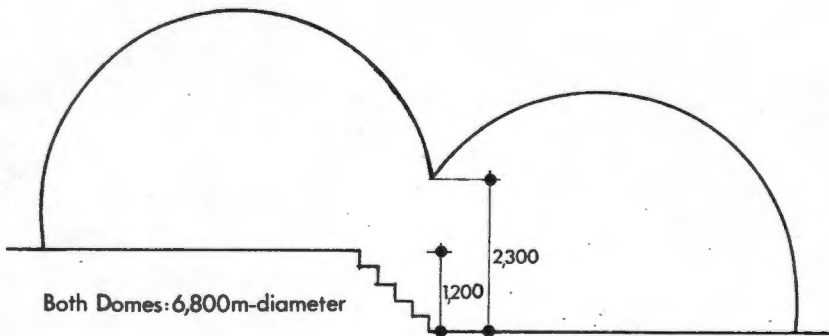


Figure 7.6 Fusion between a 5/8-Dome and a 3/8-Dome



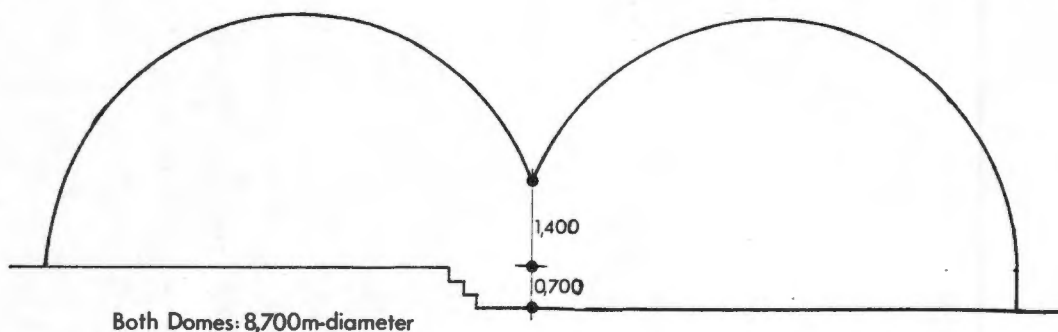
Instead of fusing one 3/8-dome and one 5/8-dome together, it is possible to fuse two 5/8-domes by building one of them on a lower level.

Figure 7.7 Fusion between two 5/8-Domes



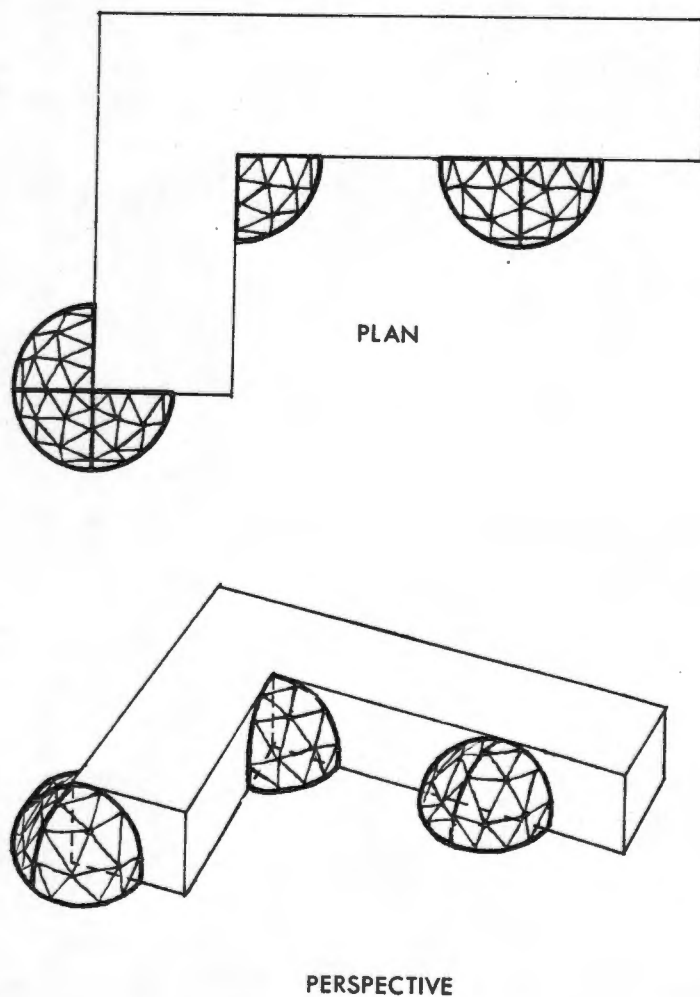
Dome C, a 4-frequency icoso-triacon hemispheric dome with an edge-zenith orientation has facets which are perpendicular to the 1/2-sphere cut-off plane - thus two similar domes will inherently have complementary vertical facets which will fuse perfectly. The fusion ring forms an apex approximately 1,4 m above the cut-off plane - in order to obtain sufficient headroom a set of steps is constructed directly below the fusion ring and the floor level of the one dome is dropped by 0,700m, with a waterproofed riser wall around the base of the dome. The formation of a raised hood involves some tricky plane intersections and should be avoided.

Figure 7.8 Fusion between two 4-frequency Icosa-Triacon Hemispheric Domes



The fusion possibilities of Dome D, a 4-frequency octa-alternate hemispheric dome, are numerous, especially when the dome is fused onto an existing  $90^\circ$ ,  $180^\circ$  or  $270^\circ$  intersection of planes (see 6.3).

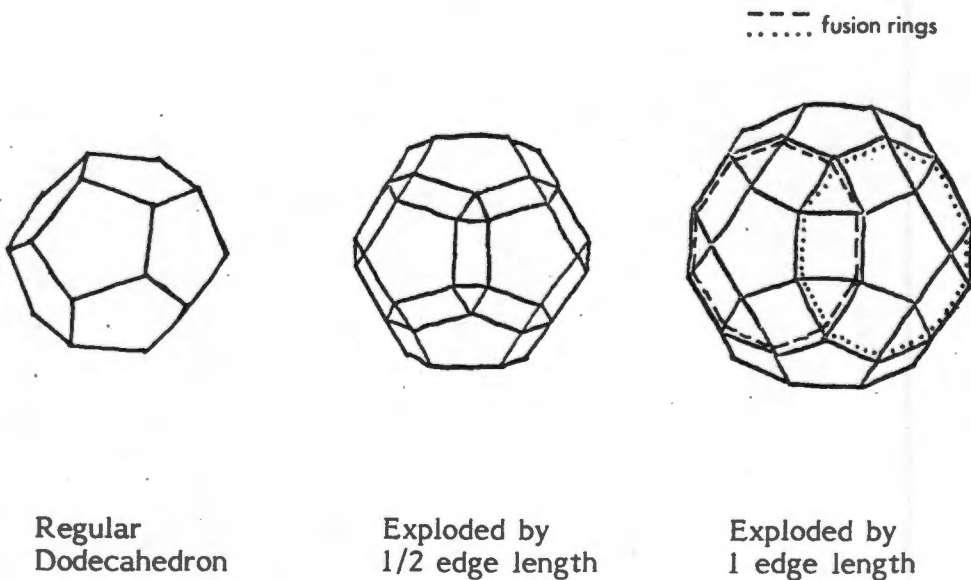
Figure 7.9 Fusion between Octa-Alternate Hemispheric Dome and Structures Manifesting  $90^\circ$ ,  $180^\circ$  and  $270^\circ$  Angles



Dome E, a Zome, has the unique feature of having 'zones' along which the zome can be expanded or contracted in a number of ways (see 6.4). In addition, there are vertical facets which will perfectly fuse two zomes.

Zomes are structures based on zonahedra, such as the cube (hexahedron), the rhombic dodecahedron and the rhombic triacontahedron (see 6.4). Each facet of a zonahedron is a zonagen with pairs of parallel edges - thus only even-sided facets are possible!

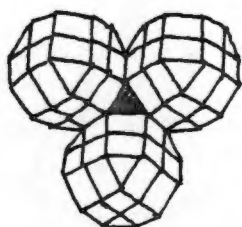
The regular dodecahedron (not a zonahedron) has twelve pentagonal facets. It may be 'exploded' by replacing its edges with rectangles and its vertexes with triangles:



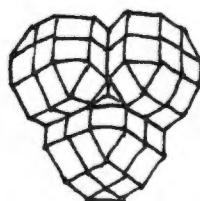
The dihedral angle (see Appendix B 5.2.3) between two planes representing overlapping fusion rings of two exploded regular dodecahedra is  $116^{\circ}34'$ , not  $120^{\circ}$  - thus the two figures will not cluster perfectly, leaving a  $3^{\circ}26'$  slice gap between them.



The rhombic dodecahedron (a zonahedron) has twelve diamond-shaped facets with a dihedral angle of  $120^\circ$  between all adjacent facets. Thus two or more rhombic dodecahedra will cluster perfectly. Exploding the rhombic dodecahedron does not change the angle between facets - thus two or more exploded rhombic dodecahedra will cluster either by kissing or by fusion.

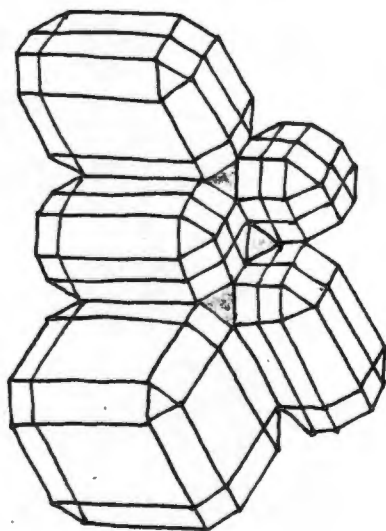


Kissing

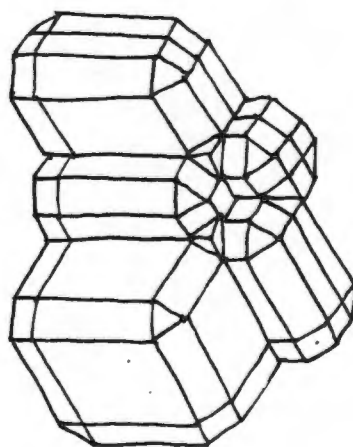


Fused

Zonahedra may be exploded by stretching zones different lengths. Below are plans of a cluster of exploded rhombic dodecahedra.



Kissing

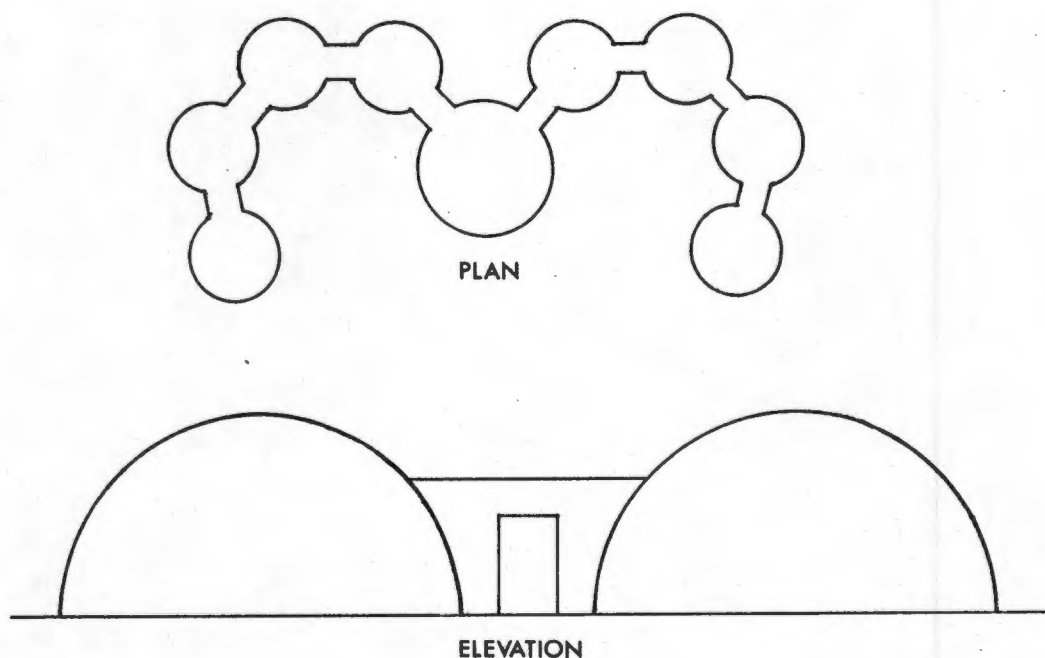


Fused

A detailed analysis of zones is beyond the scope of this study. However it becomes clearly evident that the flexibility in shape allows for unlimited design variations and cluster formations. It might suffice to say that, in practical and economic terms, zones seem to be more viable than domes.

The use of passages to connect domes together offers innumerable possibilities for any breakdown, frequency or size of dome. The major advantage of passages is that they create attractive entrance halls and the door is set into a vertical wall of the passage—this obviates the need for complicated door details to suit the spherical shape of the dome.

Figure 7.10 Passage Junction between Domes

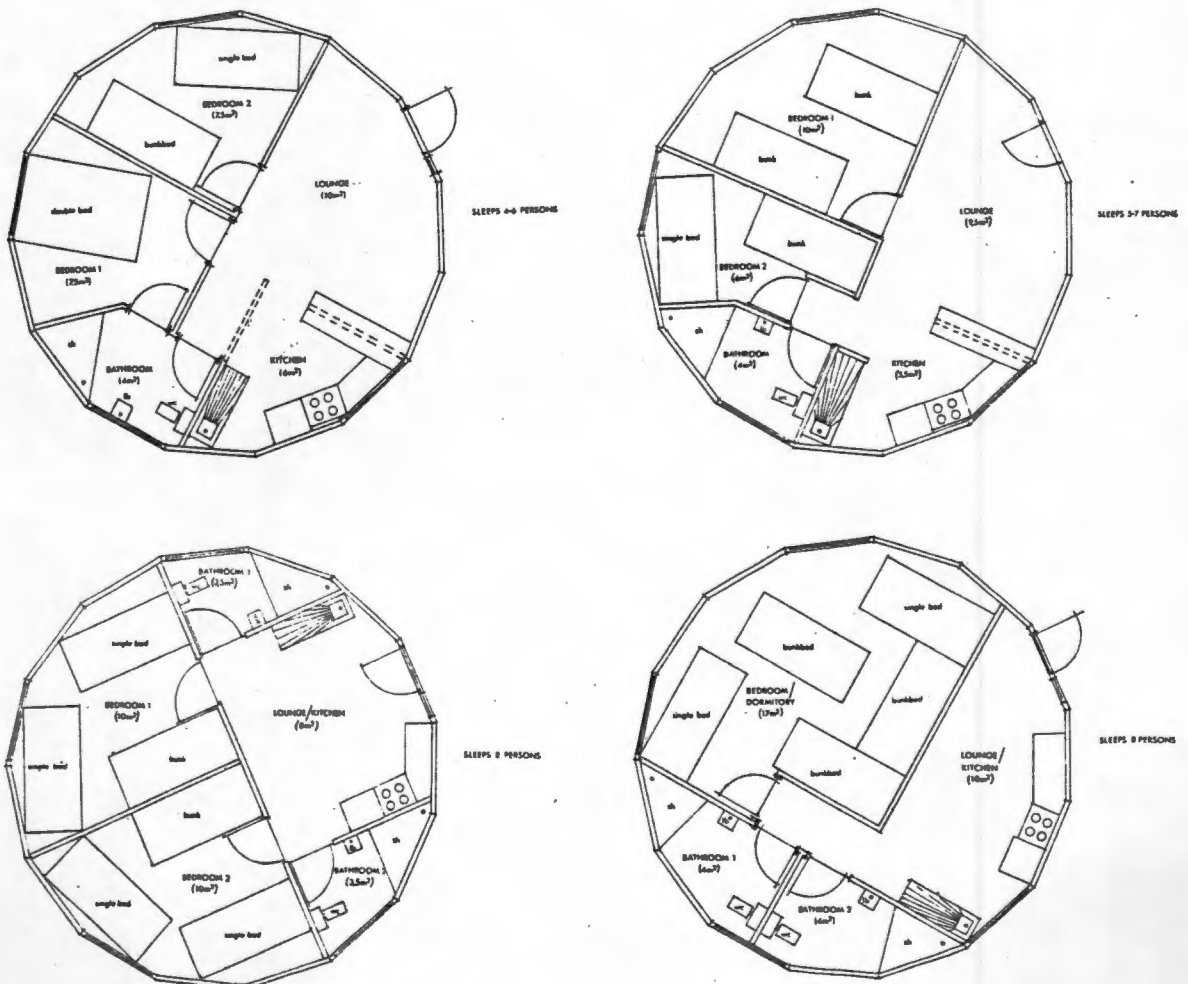


Plane intersections between two domes of different size or frequency are usually relatively complex and should be avoided. Each design must be carefully analysed in its own context and three-dimensional models must be built to determine the nestability of domes by plane intersections.

**NOTE:** Larger domes, 10 m in diameter or more, usually have sufficient volume to accommodate a mezzanine floor - thus the effective floor area is virtually doubled without the need for a nested dome.

### 7.2.4 Internal Subdivision

Within the broad context of this study, Dome A is designed merely as a volume-enclosing shell without an internal lining or ceiling and without partitions. A major criticism of domes is that the circular floor plan makes it difficult to fit modern household appliances. In order to accommodate these gadgets, the interior space of the dome should be subdivided by means of partitions which intersect at right angles (see Working Drawing No. 2). In designing the internal space subdivision of a dome, careful consideration must be taken of the effect the partitions have on the indoor thermal environment. It is suggested that to maintain the inherent environmental advantages of the spherical shape of the dome (convective flow patterns), a minimal subdivision of internal space is the optimal solution.



### 7.3 Cost Analysis

#### 7.3.1 Introduction

An economic cost analysis, although expressed in purely financial terms, must take into account the relative benefits derived from various building systems. Structural integrity, environmental performance and durability of each system must be carefully assessed as well as the ease and speed of initial construction and of possible future improvements and extensions. In broad terms, the effectiveness of various building systems can be judged by assessing not only costs thereof, but also the relative extent to which various other needs are satisfied within given resource parameters. In South Africa, for example, the benefits derived from self-help building and industrialised building far exceed the overriding financial implications. In a country where unskilled and semi-skilled labour abounds, a vast housing backlog exists (largely for the same groups of relative unskilled people), and conventional building methods cannot provide sufficient houses in terms of the present and future scale of demand, the adoption of a housing system which combines highly technological and efficient production methods with low technology on-site construction, both processes being aimed at utilizing semi-skilled and unskilled labour, and at providing new houses at a much quicker rate, creates benefits unrealised in purely financial terms. In addition certain subjective non-quantifiable benefits, such as pride in home-ownership and in achievement, a sense of self-competence and self-fulfillment, cannot be expressed in money values. It is therefore clearly very difficult to devise conceptual tools to assess the relative values people place on a heterogeneous product such as housing.

In practical terms various housing choices are expressed in terms of the physical standards of construction and related financial requirements in the provision, maintenance and running thereof.

In evaluating any new building system, a cost comparison with another system of equivalent construction standards, and the cost of which has been established by practical experience, must be undertaken. The 'geodesic kit', being a lightweight 'open industrialised' building system, is an extremely unique system in the South African context; however being aimed at the low-income housing market, the most feasible cost comparison is with the cost of the conventional 51/6 and 51/9 low income units presently being supplied on a mass scale.

Besides comparing the total cost of the systems, varying cost structures must be taken into account in order to determine the relative priority of resource input. A general cost structure comparison between the conventional building system and a 'rationalised conventional' industrialised system of building is given in the following table:

Table 7.2

|                            | <u>Conventional</u> | <u>Industrialised</u> |
|----------------------------|---------------------|-----------------------|
| Capital depreciation costs | 1%                  | 15%                   |
| Labour costs               | 45%                 | 25%                   |
| Materials costs            | 44%                 | 50%                   |
| Profit                     | 10%                 | 10%                   |

Various rationalised conventional industrialised building systems are widely employed in South Africa. 'Open industrialised' systems are also used, but on a very limited scale, and almost exclusively in the heavyweight division; the 'geodesic kit' falls within the 'lightweight' category. Although the overall cost structure of various industrialised systems does not vary substantially, the differing labour and material inputs on a micro level requires each system to be evaluated separately without prejudice towards preconceived norms and averages.



### 7.3.2 Labour Cost Calculations

The calculation of material costs is relatively simple (see 7.3.3): however labour costs are much more difficult to predict with extreme accuracy without an extensive work study analysis on the practical application of a particular system. The 'geodesic kit' inherently has a unique labour cost structure - the following calculations are based merely on experience gained from the practical construction of prototype Dome A, in conjunction with some 'educated guesswork'.

Two major considerations must be taken into account:

- The composition of the labour force varies, depending on whether the building project involves the construction of a one-off structure ('self-help' is an example, where one 'team' constructs the whole dwelling unit), or whether a number of completed mass-produced units are constructed by a large organisation with 'specialised teams' for various operations.
- A careful distinction must be made between factory labour requirements and on-site labour. Extensive training programmes are necessary to produce the required mix of skills, from management to unskilled labour. The bias in most industrialised systems (as with the 'geodesic kit') is towards more management and supervisory skills, as well as semi-skilled operatives, in lieu of skilled labour. The transmission to an uneducated workforce of the basic skills employed in an uniquely different building ethic to that generally encountered in conventional building practice, is a process requiring extensive training programmes, with graphically-illustrated manuals and colour-coded assembly details, as well as close on-site supervision (see 5.4.3).

The on-site operations and labour requirements are further divided into:

- Foundations, and

- Superstructure.

The main reasons for this division are twofold:

- In suggesting that the 'geodesic kit' is ideally suited to 'self-help' building, it is assumed that only the superstructure can be erected by individual 'self-help' builders; as stated previously, the foundations should preferably be constructed by specialists until such time as a completely pre-manufactured foundation kit is devised, requiring low-technology on-site construction. At this stage the foundations are constructed by the relatively conventional means of in-situ concrete casting. The pre-casting of concrete footings in sections and the construction of 'peach-pip and cow-dung' floors enhances low-technology on-site construction with concomitant cost savings and possible self-help foundation construction.
- A distinct difference in required labour skills exists between the two stages of on-site construction. Thus separate labour gangs are necessary and separate cost structures may be identified.

In broad terms the overall labour cost structure is thus categorised into three groups:

- Manufacture: in factory;
- Foundation Construction: on site;
- Superstructure Assembly: on site.

### 7.3.2.1 Manufacture

The process of manufacture entails five distinct operations:

- 1 Cut timber
- 2 Drill timber
- 3 Manufacture 'standard shell' frames
- 4 Manufacture 'special' frames
- 5 Fix sheet cladding to frames.

In order to eliminate unproductive time, the work content of each operation must be carefully established; then labour is allocated to each operation so that different gangs take approximately the same period of time to complete an operation. The cycle time for factory operations is 8 hours or one working day, as is shown in Schedule 7.1.

Schedule 7.1 Manufacture of One Dome-Kit

| Operation                                   | Minimum<br>Gang Size      | Work<br>Content<br>(in hours) | Actual<br>Gang Size         | Duration<br>(Cycle Time)<br>(in hours) |
|---|---------------------------|-------------------------------|-----------------------------|--|
| 1 Cut timber                                | 1 Operative<br>1 Labourer | 16                            | 2 Operatives<br>2 Labourers | 8                                      |
| 2 Drill timber                              | 1 Operative<br>1 Labourer | 8                             | 1 Operative<br>1 Labourer   | 8                                      |
| 3 Manufacture<br>'Standard Shell'<br>frames | 1 Joiner<br>1 Labourer    | 16                            | 2 Joiners<br>2 Labourers    | 8                                      |
| 4 Manufacture<br>'Special'<br>frames        | 1 Joiner<br>1 Labourer    | 16                            | 2 Joiners<br>2 Labourers    | 8                                      |
| 5 Fix cladding                              | 1 Operative<br>1 Labourer | 8                             | 1 Operative<br>1 Labourer   | 8                                      |

Programme 7.1 illustrates the proposed manufacture of 10 dome-kits by one team consisting of:

- 1 Foreman
- 4 Operatives
- 4 Joiners
- 8 Labourers

Programme 7.1 Manufacture of 10 Dome-Kits

| Operation         | Days  | 1 | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13  |
|-------------------|-------|---|----|----|----|----|----|----|----|----|----|----|----|-----|
|                   | Hours | 8 | 16 | 24 | 32 | 40 | 48 | 56 | 64 | 72 | 80 | 88 | 96 | 104 |
| 1 Cut timber      |       | 1 | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |    |    |     |
| 2 Drill timber    |       |   |    |    |    |    |    |    |    |    |    |    |    | 10  |
| 3 Standard frames |       |   |    |    |    |    |    |    |    |    |    |    |    | 10  |
| 4 Special frames  |       |   |    |    |    |    |    |    |    |    |    |    |    | 10  |
| 5 Fix cladding    |       |   |    |    |    |    |    |    |    |    |    |    |    | 10  |

- According to the above programme, one factory team will manufacture 10 domes in 13 working days.
- The labour cost per team for the manufacture of 10 domes is thus calculated as follows:

|     |           |     |   |        |   |                 |
|-----|-----------|-----|---|--------|---|-----------------|
| 104 | Foreman   | hrs | @ | R10,00 | = | R1040,00        |
| 320 | Joiner    | hrs | @ | R 6,00 | = | R1920,00        |
| 320 | Operative | hrs | @ | R 4,00 | = | R1280,00        |
| 640 | Labourer  | hrs | @ | R 2,00 | = | R1280,00        |
|     |           |     |   |        |   | <u>R5520,00</u> |

Thus, factory labour cost per dome is R 552,00

As the same team manufactures more domes, marginal costs decrease, as supervisory labour costs (foreman) are spread over an increasing number of units. In addition increasing labour productivity should be realised due to a 'learning curve'. The labour cost for 100 domes manufactured by one team in 103 days, is calculated as follows:

|                      |        |   |                  |
|----------------------|--------|---|------------------|
| 103 Foreman days @   | R80,00 | = | R 8240,00        |
| 400 Joiner days @    | R48,00 | = | R19200,00        |
| 400 Operative days @ | R32,00 | = | R12800,00        |
| 800 Labourer days @  | R16,00 | = | R12800,00        |
|                      |        |   | <u>R53640,00</u> |

Thus, factory labour cost per dome is reduced to R536,40

#### 7.3.2.2 Foundations

The following operations are involved in the construction of foundations:

- 1 Set out
- 2 Fix shutters
- 3 Dig trenches
- 4 Cast concrete footings
- 5 Level and compact earthfilling\*; place, level and compact sandbed; and lay damp-proofing membrane
- 6 Cast concrete surface bed\*\*

\* Of the 3 m<sup>3</sup> of earthfill required per dome, 1 m<sup>3</sup> is provided from trench excavations. For compaction a mechanical compactor is assumed to be necessary.

\*\* Approximately two hours after casting surface bed concrete, the bed should be power floated to produce a smooth surface - alternatively a screed is necessary. In drawing up a programme for the



repetitive construction of a number of domes with power-floated floors, close attention must be paid to the critical time-dependence between casting of concrete and floating. The concreting gang should cast surface beds only for the first half (4 hours) of each working day to avoid overtime on floating. During the latter half of the day, the same concreting gang is kept busy by casting the footings of the next unit. It may be noticed from Schedule 7.2 that the two concreting operations entail similar durations, resulting in a perfectly balanced programme.

Due to the critical time dependence and also the skill required to operate a power-float, the use of screeded floors is preferred, especially for lower-cost construction and self-help building. However the following programmes include floated floors to illustrate the importance of careful planning.

Schedule 7.2 Foundation Construction of One Dome

| Operation                     | Labour Gang  | Duration (in hrs) |
|-------------------------------|--|-------------------|
| 1 Set out                     | 1 Foreman<br>1 Labourer                            | 1                 |
| 2 Fix shutters                | 2 Carpenters<br>2 Labourers                        | 2                 |
| 3 Dig trenches                | 1 Gang boss<br>6 Labourers                         | 2                 |
| 4 Cast concrete footings      | 1 Gang boss<br>6 Labourers                         | 2                 |
| 5 Earthfill<br>Sandbed<br>DPM | 1 Gang boss<br>1 Compactor operator<br>4 Labourers | 2                 |
| 6 Cast concrete surface bed   | 1 Gang boss<br>6 Labourers                         | 2                 |
| 7 Power-float                 | 1 Operator<br>2 Labourers                          | 2                 |

NOTES:

- Operations 4 and 6 are executed by the same gang to avoid over-time on floating. In order to balance gangs, operations 3 and 5 are also executed by one gang.
- It is assumed that all concrete is machine-mixed on site; however the use of ready-mixed concrete does not alter the overall cost substantially, as material and labour costs offset each other. The programme may be affected, since the use of ready-mixed concrete could reduce the cycle time of this critical operation.

Programme 7.2(A) illustrates the construction of foundations for 10 domes by one team consisting of:

- 1 Foreman
- 2 Carpenters
- 2 Operators
- 2 Gang Bosses
- 14 Labourers

Programme 7.2(A) Foundation Construction of 10 Domes

| Operation         | Days  |                      |     |     |          |      |    |    |
|-------------------|-------|----------------------|-----|-----|----------|------|----|----|
|                   | Hours | 1                    | 2   | 3   | 4        | 5    | 6  | 7  |
|                   |       | 8                    | 16  | 24  | 32       | 40   | 48 | 56 |
| 1 Set-out         |       | 1 2 3 4 5 6 7 8 9 10 |     |     |          |      |    |    |
| 2 Fix shutters    |       | 1 2 3 4 5 6 7 8 9 10 |     |     |          |      |    |    |
| 3 Dig trenches    |       | 1 2 3 4              | 5 6 | 7 8 | 9 10     |      |    |    |
| 4 Cast footings   |       | 1 2 3 4              | 5 6 | 7 8 | 9 10     |      |    |    |
| 5 Earthfill, etc. |       | 1 2                  | 3 4 | 5 6 | 7 8 9 10 |      |    |    |
| 6 Surface bed     |       | 1 2                  | 3 4 | 5 6 | 7 8      | 9 10 |    |    |
| 7 Power-float     |       | 1 2                  | 3 4 | 5 6 | 7 8      | 9 10 |    |    |

- According to Programme 7.2(A), one team completes 10 foundations in 7 days.
- Labour cost per 10 domes:

|     |           |     |   |        |   |                 |
|-----|-----------|-----|---|--------|---|-----------------|
| 56  | Foreman   | hrs | @ | R10,00 | = | R 560,00        |
| 40  | Carpenter | hrs | @ | R 6,00 | = | R 240,00        |
| 72  | Operator  | hrs | @ | R 3,00 | = | R 216,00        |
| 80  | Gang boss | hrs | @ | R 3,00 | = | R 240,00        |
| 522 | Labourer  | hrs | @ | R 2,00 | = | R1044,00        |
|     |           |     |   |        |   | <u>R2300,00</u> |

Thus, labour cost per dome foundation is R230

The above programme shows that the foreman, besides setting-out the dome foundations, supervises too little labour because:

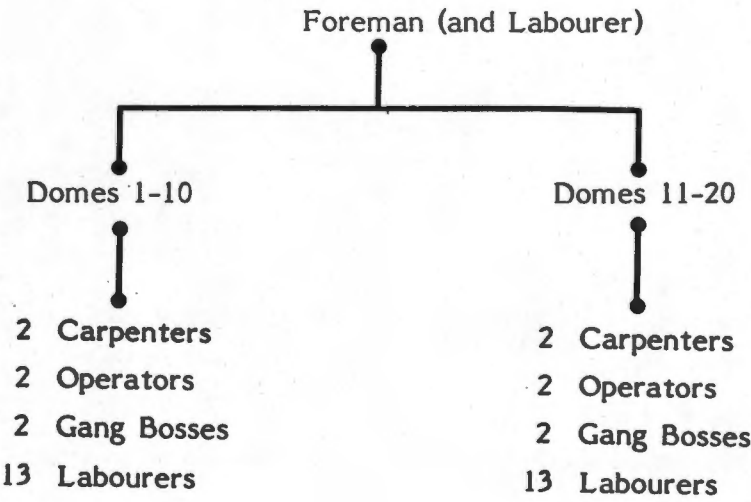
- of the 14 labourers, four are in the excavating gang and six in the concreting gang, with a gang boss per gang - thus the foreman only needs to check intermittently on workmanship and progress.
- only three or four operations occur simultaneously at any time e.g. during the first two hours on working day 5, the formwork gang is busy on dome 8, the excavating gang is busy on dome 6 (doing 'earthfill, etc.' - the same gang does the two operations 'excavate trenches' and 'earthfill, etc.') and the concreting gang is busy on dome 5 (casting surface bed concrete).

Thus to employ the foreman more productively, the size of his labour team is doubled - consequently the team's output increases from 10 to 20 dome foundations per 7 working days.

The new team consists of:

- 1 Foreman
- 4 Carpenters
- 4 Operators
- 4 Gang bosses
- 27 Labourers (not 28, because the 'setting out' labourer works twice as long as before)

New Team Structure



Programme 7.2(B) illustrates the construction of foundations for 20 domes by the new team.

| Operation        | Days  | 1                    | 2   | 3   | 4        | 5   | 6    | 7  |
|------------------|-------|----------------------|-----|-----|----------|-----|------|----|
|                  | Hours | 8                    | 16  | 24  | 32       | 40  | 48   | 56 |
| 1 Set out        |       | 1 2 3 4 5 6 7 8 9 10 |     |     |          |     |      |    |
| 2 Fix shutters   |       | 1 2 3 4 5 6 7 8 9 10 |     |     |          |     |      |    |
| 3 Dig trenches   |       | 1 2 3 4              | 5 6 | 7 8 | 9 10     |     |      |    |
| 4 Cast footings  |       | 1 2 3 4              | 5 6 | 7 8 | 9 10     |     |      |    |
| 5 Earthfill etc. |       | 1 2                  | 3 4 | 5 6 | 7 8 9 10 |     |      |    |
| 6 Surface bed    |       |                      | 1 2 | 3 4 | 5 6      | 7 8 | 9 10 |    |
| 7 Power-float    |       |                      | 1 2 | 3 4 | 5 6      | 7 8 | 9 10 |    |
| 1 Set out        |       | 1 2 3 4 5 6 7 8 9 10 |     |     |          |     |      |    |
| 2 Fix shutters   |       | 1 2 3 4 5 6 7 8 9 10 |     |     |          |     |      |    |
| 3 Dig trenches   |       | 1 2 3 4              | 5 6 | 7 8 | 9 10     |     |      |    |
| 4 Cast footings  |       | 1 2 3 4              | 5 6 | 7 8 | 9 10     |     |      |    |
| 5 Earthfill etc. |       | 1 2                  | 3 4 | 5 6 | 7 8 9 10 |     |      |    |
| 6 Surface bed    |       |                      | 1 2 | 3 4 | 5 6      | 7 8 | 9 10 |    |
| 7 Power-float    |       |                      | 1 2 | 3 4 | 5 6      | 7 8 | 9 10 |    |

● Labour cost per 20 domes:

|               |     |          |                 |
|---------------|-----|----------|-----------------|
| 56 Foreman    | hrs | @ R10,00 | = R 560,00      |
| 80 Carpenter  | hrs | @ R 6,00 | = R 480,00      |
| 144 Operator  | hrs | @ R 3,00 | = R 432,00      |
| 160 Gang boss | hrs | @ R 3,00 | = R 480,00      |
| 1044 Labourer | hrs | @ R 2,00 | = R2088,00      |
|               |     |          | <u>R4040,00</u> |

Thus, labour cost per dome foundation is reduced to R202



## NOTES:

- The same team as the one constructing 20 dome foundations in 7 working days at a cost of R202 per dome, will complete 100 dome foundations in 27 working days at a cost of R196 per dome.
- The screeding of unfloated surface beds takes one plasterer and two labourers one working day (or 8 working hours) per dome. The programme is more flexible, as the critical dependence between casting of surface bed concrete and floating is eliminated.

7.3.2.3 Superstructure

The following operations are involved in the assembly of the superstructure:

- 1 Assemble 'Standard shell'
- 2 Assemble 'Special' panels
- 3 Seal joints
- 4 Paint and finish

Schedule 7.3 Superstructure Assembly per Dome

| Operation                   | Labour Gang                 | Duration (in hrs) |
|-----------------------------|-----------------------------|-------------------|
| 1 Assemble 'Standard shell' | 1 Operative<br>2 Labourers  | 8                 |
| 2 Assemble 'Special' panels | 1 Operative<br>2 Labourers  | 8                 |
| 3 Seal joints               | 2 Operatives<br>2 Labourers | 8                 |
| 4 Paint and finish          | 2 Operatives<br>2 Labourers | 8                 |

The labour used is semi-skilled and unskilled - thus extremely close supervision is of utmost importance. Each labour team consists of:

- 1 Foreman/Supervisor
- 6 Operatives
- 8 Labourers

NOTE: One gang, consisting of two operatives and two labourers (or one family) can assemble and finish the dome superstructure in four working days.

Programme 7.3 illustrates the assembly of 10 domes by one team of labour:

| Operations         | Days  | 1 | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13  |
|--------------------|-------|---|----|----|----|----|----|----|----|----|----|----|----|-----|
|                    | Hours | 8 | 16 | 24 | 32 | 40 | 48 | 56 | 64 | 72 | 80 | 88 | 96 | 108 |
| 1 'Standard shell' |       | 1 | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |    |    |     |
| 2 'Special' panels |       |   |    |    |    |    |    |    |    |    |    |    |    | 10  |
| 3 Seal joints      |       |   |    |    |    |    |    |    |    |    |    |    |    | 10  |
| 4 Paint and finish |       |   |    |    |    |    |    |    |    |    |    |    |    | 10  |

- One team assembles 10 domes in 13 working days
- Labour cost per 10 domes:

|     |           |     |   |        |   |                 |
|-----|-----------|-----|---|--------|---|-----------------|
| 104 | Foreman   | hrs | @ | R10,00 | = | R1040,00        |
| 480 | Operative | hrs | @ | R 3,00 | = | R1440,00        |
| 640 | Labourer  | hrs | @ | R 2,00 | = | R1280,00        |
|     |           |     |   |        |   | <u>R3760,00</u> |

Thus labour cost in assembling one dome superstructure is R376,00

- One team will assemble 100 domes in 103 working days
- Labour cost per 100 domes:

|     |           |      |   |        |   |                  |
|-----|-----------|------|---|--------|---|------------------|
| 103 | Foreman   | days | @ | R80,00 | = | R 8240,00        |
| 600 | Operative | days | @ | R24,00 | = | R14400,00        |
| 800 | Labourer  | days | @ | R16,00 | = | R12800,00        |
|     |           |      |   |        |   | <u>R35440,00</u> |

Thus labour cost in assembling one dome is reduced to R354,40

Due to a learning cycle it is assumed that operatives and labourers will require less supervision as they become more familiar with their respective tasks. Once a well-trained labour force is in operation, each foreman could supervise two teams each assembling 10 domes in 13 working days or 100 domes in 103 working days.

- Labour cost per 20 domes: (10 per team)

|      |           |     |   |        |   |                 |
|------|-----------|-----|---|--------|---|-----------------|
| 104  | Foreman   | hrs | @ | R10,00 | = | R1040,00        |
| 960  | Operative | hrs | @ | R 3,00 | = | R2880,00        |
| 1280 | Labourer  | hrs | @ | R 2,00 | = | R2560,00        |
|      |           |     |   |        |   | <u>R6480,00</u> |

Thus labour cost per dome superstructure is R324,00

- Two trained teams will assemble a total of 100 domes in 53 working days
- Labour cost per 100 domes:

|     |           |      |   |        |   |                  |
|-----|-----------|------|---|--------|---|------------------|
| 53  | Foreman   | days | @ | R80,00 | = | R 4240,00        |
| 600 | Operative | days | @ | R24,00 | = | R14400,00        |
| 800 | Labourer  | days | @ | R16,00 | = | R12800,00        |
|     |           |      |   |        |   | <u>R31440,00</u> |

Thus labour cost per dome superstructure is R314,40

It is suggested that in a contract of 100 domes or more four trained teams under the supervision of two foremen are employed so that the cycle time of 27 days corresponds with the cycle time for the construction of 100 dome foundations.

#### 7.3.2.4 Summary of Total Labour Cost per Dome

- In a contract of 10 Domes:

|                |              |
|----------------|--------------|
| Manufacture    | R 552        |
| Foundations    | R 230        |
| Superstructure | <u>R 376</u> |
| TOTAL          | <u>R1158</u> |

- In a contract of 100 Domes:

|                |              |                |                        |
|----------------|--------------|----------------|------------------------|
| Manufacture    | R 537        | (R 537)        |                        |
| Foundations    | R 196        | (R 196)        |                        |
| Superstructure | <u>R 355</u> | <u>(R 315)</u> | (trained labour force) |
| TOTAL          | <u>R1088</u> | <u>(R1048)</u> |                        |

7.3.3 Materials Schedule

| Material description   | Unit              | Quantity | Price<br>(in R) | Cost<br>(in R) |         |
|--|-------------------|----------|-----------------|----------------|---------|
| ● <u>Manufacture:</u>  |                   |          |                 |                |         |
| 20x70 mm S.A. Pine PAR   | m                 | 400      | 0,80            | 320,00         |         |
| 70x70 mm S.A. Pine PAR   | m                 | 15       | 3,10            | 46,50          |         |
| 20x108 mm S.A. Pine PAR  | m                 | 25       | 1,20            | 31,25          |         |
| 32x108 mm S.A. Pine PAR  | m                 | 25       | 1,85            | 46,25          |         |
| 38x38 mm sawn S.A. Pine  | m                 | 60       | 1,00            | 60,00          |         |
| N43FX 'Woodlyte' window<br>frame   | No.               | 4        | 85,00           | 34,00          |         |
| DFH38 'Woodlyte' door<br>frame   | No.               | 1        | 30,00           | 30,00          |         |
| FLB door   | No.               | 1        | 60,00           | 60,00          |         |
| Ironmongery (lock-set and<br>hinges)   | No.               | 1        | 25,00           | 25,00          |         |
| 8x40 mm brass screws   | No./200           | 10       | 10,00           | 100,00         |         |
| 9 mm FRC 'weatherboard'<br>1,200x3,000 m sheets                                    | No.               | 30       | 30,00           | 900,00         |         |
| 3 mm clear sheet glass   | m <sup>2</sup>    | 4        | 18,00           | 72,00          |         |
| Sundries (glue, nails, etc.)   |                   |          |                 | 69,00          | 2100,00 |
| ● <u>Foundations:</u>  |                   |          |                 |                |         |
| 38x38 mm sawn S.A. Pine  |                   | 50       | 1,00            | 50,00          |         |
| 21x150 mm formboard  | m                 | 40       | 2,25            | 90,00          |         |
| 10 MPa concrete (19 mm<br>stone; 75 mm slump)                                      | m <sup>3</sup>    | 4        | 70,00           | 280,00         |         |
| *(3:1 c.m. screed)   | (m <sup>3</sup> ) | (1)      | (50,00)         | (50,00)        |         |
| USB green DPM  | m <sup>2</sup>    | 50       | 1,20            | 60,00          |         |
| 350 mm long hookbolts  | No.               | 60       | 0,40            | 24,00          |         |
| Sundries   |                   |          |                 | 46,00          | 550,00  |
| *No screed required with power-floated surface beds                                |                   |          |                 |                |         |
| ● <u>Superstructure:</u>   |                   |          |                 |                |         |
| 8 mm-diameter 50 mm long<br>galvanised bolts with<br>a nut and two flat<br>washers | No./100           | 4        | 20,00           | 80,00          |         |
| 'Bidim' U-14 geofabric   | m <sup>2</sup>    | 50       | 1,00            | 50,00          |         |
| 'Viaseal' rubberised bitumen   | 25 l              | 4        | 50,00           | 200,00         |         |
| 'Klodek' acrylic emulsion<br>paint   | 25 l              | 2        | 75,00           | 150,00         |         |
| Sundries (brushes, etc.)   |                   |          |                 | 70,00          | 550,00  |
| TOTAL MATERIAL COST  |                   |          |                 |                | 3200,00 |
| + G.S.T.   |                   |          |                 |                | 320,00  |
|  |                   |          |                 |                | 3520,00 |



### 7.3.4 Summary of Costs per Dome

|                  | <u>Material Cost</u><br>(in R) | <u>* Labour Cost</u><br>(in R) | <u>Total Cost</u><br>(in R) |
|------------------|--------------------------------|--------------------------------|-----------------------------|
| • Manufacture    | 2100                           | 535                            | 2635                        |
| • Foundations    | 550                            | 200                            | 750                         |
| • Superstructure | 550                            | 315                            | 865                         |
|                  | <u>3200</u>                    | <u>          </u>              | <u>4250</u>                 |
| G.S.T.           | 320                            | <u>          </u>              | 320                         |
|                  | <u>3520</u>                    | <u>1050</u>                    | <u>4570</u>                 |
|                  | (77%)                          | (23%)                          | (100%)                      |

\* for the construction of 100 domes with a trained labour force.

Dome A has a floor area of 35 m<sup>2</sup> at a material and labour cost of R130 per m<sup>2</sup>.

### Total Cost Structure

|                        |              |               |  |
|------------------------|--------------|---------------|--|
| * Capital depreciation | R 830        | (14%)         | * includes cost of:<br>i) establishing factory<br>ii) allplant: factory and site<br>iii) training programmes |
| Materials              | R3520        | (58%)         |  |
| Labour                 | R1050        | (18%)         |  |
| Overheads and Profit   | R 600        | (10%)         |  |
|                        | <u>R6000</u> | <u>(100%)</u> |  |

Total cost per m<sup>2</sup> of Dome A is R170.



## CONCLUSION

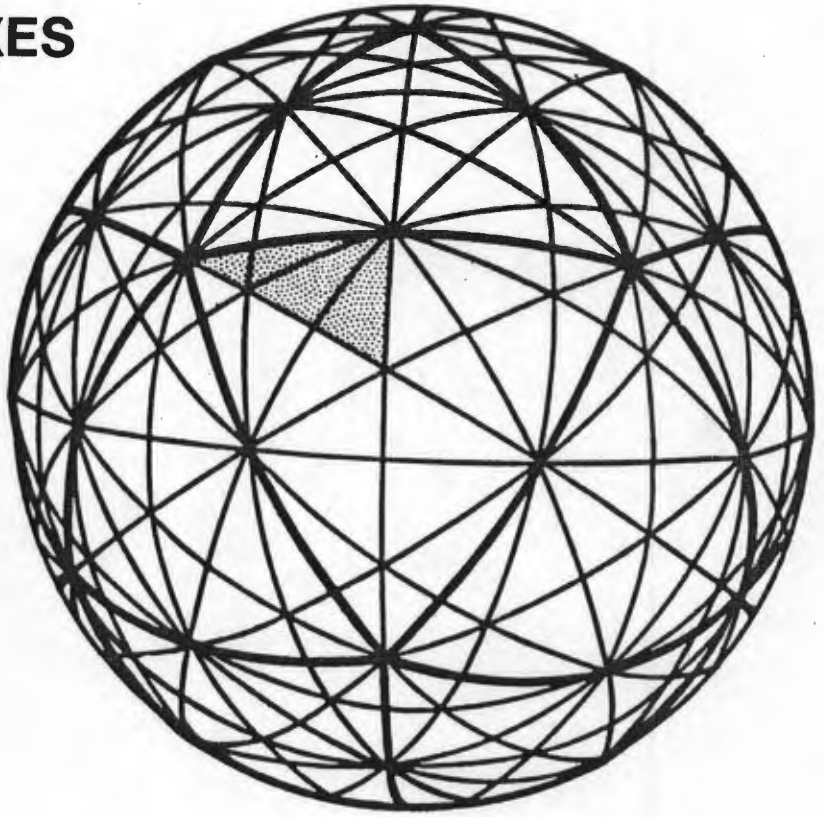
In South Africa, an industrial-based economy has developed, with a bias towards high technology - First World technology. However, experience and knowledge of a well-developed Third World low technology lies dormant amongst the largest sector of the population. Perhaps these two diverse technologies should be combined in a fairer marriage, so that low technology can feed on high technology, with high technology providing a platform from which low technology can operate.

Present high technology domination and inadequate education and training facilities to support this approach, means that most of the population is excluded from participating in the economic system that governs their life, resulting in unfulfilled, unstable and agitated communities. It is human nature to eventually reject what is handed over on a plate, especially when the serving is unappetising.

The necessity for low-technology development is apparent when the reality of the situation is faced: there is a rapidly growing unskilled and semi-skilled labour force emerging, while technology is developing at a level way beyond the technical and economic capabilities of the population. A closer relationship between man and his urban environment and the economy, created by a successful marriage between low and high technology, may be achieved through the housing process. Both conventional and traditional methods of house construction cannot provide

according to the required scale of demand, in terms of technical, financial and natural resources; however an industrialised lightweight housing system, using high technology manufactured components to allow for low technology on-site erection, results in an ideal mix of required skills and represents a system which can provide more houses at an unprecedented rate of output and possibly even at an affordable price.

## APPENDIXES





## APPENDIX A

### Supplement to Section A (Chapters 1 and 2)

#### A. A BRIEF HISTORICAL ACCOUNT OF BANTU MIGRATIONS AND SETTLEMENTS IN SOUTHERN AFRICA

##### A.1 Introduction

In order to clearly understand the scattered and seemingly random geographical location of the various tribal homelands or independent Southern African Black States, and the traditional house form and construction techniques in these areas, one must analyse early black migrations and settlement, broad tribal and cultural affiliation, and the degree of cross-cultural contamination.

The enormous population growth amongst the negroid population of central-east Africa caused vast masses of people to migrate southwards in search of sufficient land and pastures to support their large herds of cattle. A number of broad groupings may be linguistically and culturally defined. The largest of these are the Nguni and the Sotho-Tswana, with two smaller ones, the Tsonga and Venda. Of the 20 million blacks presently living south of the Limpopo, approximately 66 per cent are Nguni-speakers and 28 per cent are of Sotho-Tswana stock.<sup>1</sup>

## A.2 Early Migration and Settlements

The Sotho-Tswana-speakers are believed to have been the first blacks to cross the Zambesi river into Botswana and to migrate further southwards across the Limpopo river. Chronologically they arrived in three waves. The first to arrive were two unrelated groups, the Kgalaghari, (a tribe possibly associated originally with the Galla tribe from Kenya or the Shao Gala from Ethiopia and after which the Kalahari desert was probably named) and the Fokeng. They were followed by the ancestors of the Thlaping and the Rolong, whose founder-hero was Morolong. These Tswana-speakers today reside mainly in Botswana and Bophuthatswana and only constitute about 8 per cent (1,5 million persons) of the total black population south of the Limpopo river.

The last wave, much larger than the previous two, crossed the Limpopo in the fifteenth or early sixteenth century. It consisted of Sotho-speakers of the Hurutshe, Kwena and Khatla lineages, including the chiefdoms of Ngwato, Pedi, Tlokwa and others, whose founder-hero was Mangope. Being herdsmen, they could not settle in areas heavily infested with tsetse-fly - they were thus cut off from the coast by a tsetse-fly belt which stretched along the foothills of the Drakensberg. Consequently they settled in the highveld regions of the present Transvaal, Orange Free State, Northern Cape and in-and-around Swaziland; presently they represent about 20 per cent (4 million persons) of the total black population south of the Limpopo, being almost equally divided between North Sotho and South Sotho.

The origin of the Nguni-speakers is unclear and open to much speculation. It is assumed that they migrated through Botswana across the Limpopo river early in the sixteenth century. On finding the Sotho-Tswana settled

on the Transvaal highveld, they were forced towards the coast. The Embo section, consisting of Ngwane, Ndwandwe, Hlubi, Dlamini and others, soon moved eastwards, settling for a while in the region of present-day Kangwane and in Swaziland where they came into contact with the Sotho-speakers already living there. They eventually crossed over the Lebombo mountains into Tsonga country, where their language became 'tekelised'. However myths of origins vary and some believe that they originally came down from the north-west. However by the end of the sixteenth century they had moved southwards and settled down in a region stretching from Swaziland past the upper Pongola river to the Buffalo river in the south.<sup>2</sup>

The Ntungwa (mainly Zulu) and the Xhosa sections of the Nguni-speakers moved southwards from the highveld across the Drakensberg. By the latter half of the sixteenth century the Ntungwa had settled down around the Tugela river and the Xhosa further south in present-day Transkei.<sup>3</sup> Two other tribes, the Thembu and the Mpondo also moved south-westwards into the Transkei. It is however not clear whether they were affiliated to the Embo clan as oral tradition may suggest<sup>4</sup> or whether they belonged to the Xhosa whose language they spoke. The Mpondo settled in the northern Transkei, the Thembu further south, eventually pushing some Xhosa across the Kei river as far south as the Bushman's river, notably the Ngqika who settled in present-day Ciskei and the Gcaleka a little further north. Today the Nguni-speakers are broadly classified into two distinct groups according to cultural and linguistic tradition:

- Northern Nguni e.g. Zulu, Swazi (Ngwane and Dlamini), Ndebele - they represent approximately 33 per cent (nearly 7 million persons) of the total black population south of the Limpopo.
- Southern Nguni e.g. Xhosa, Thembu, Mpondo - they also represent 33 per cent of the black population south of the Limpopo.

Having completed their long journey from the north, these nomadic herds-men changed to a semi-sedentary way of life. Consequently their houses and settlements became more permanent and traditional architecture was developed over the next four centuries (see 1.2).

### A.3 Cross-cultural Contamination

The early nomadic - and later semi-sedentary - way of life of southern Africa's indigenous blacks inherently led to cross-tribal contact and subsequent cultural contamination. Traditional house forms were married to adapt mainly to the local climate and availability of materials in various locations of settlements (see 1.2).

In addition, forced migration due to inter-tribal aggression frequently led retreating tribes into neighbouring land. Early in the nineteenth century inter-tribal conflict occurred on an unprecedented scale. Even before the 'Difaqane' hostility and bloody warfare abounded with land becoming increasingly scarce and valued. Apart from the direct conflict amongst the blacks in the north-eastern areas of southern Africa, bitter land disputes between the blacks and the frontier of trekboers and Voortrekkers, advancing from the south-west, occurred.

The first evidence of a party of whites from the settlement at the Cape making contact with the southernmost black tribe, the Xhosa, was in 1702.<sup>5</sup> Over the next century the power of the Xhosa chiefs diminished with successive defeats and loss of land. However only after the Difaqane did the Voortrekkers join in the previously all-tribal conflict in the north-eastern regions.

The black-white confrontation usually resulted in white gain at the expense of the black, due to the former's superior weapons and dominating

technology. As a result traditional black house-forms became increasingly contaminated by Western technology.

#### A.4 The Difaqane and its aftermath

At the turn of the nineteenth century the following black chiefdoms, amongst other, were spread across southern Africa:

- Mthethwa - under Dingiswayo
- Ndwandwe - under Zwide
- Hlubi - under Mtikulu (Mpangazita's father)
- Ngwane - under Matiwane
- Dlamini - under Ndungunya (Sobuza I's father)
- Zulu - under Senzangakhona (Shaka's father)
- Khumalo - under Mashobane (Mzilikatzi's father)
- Pedi - under Thulare (Sekwati's father)
- Kweni - under Mokhachane (Moshweshwe's father)
- Tlokwa - under MaNthatisi (Sekonyela's mother)
- Xhosa - under Hintsa (a Gcaleka chief)
- Thembu - under Ngubencuka (Matanzima I's grandfather and five generations before the present Chief Minister of the Transkei)
- Mpondo - under Ngqungqushu (Faku's father)

The roots of the upheaval which eventually led to the Difaqane wars (or Mfecane) in the 1820's were planted by Dingiswayo chief of the Mthethwa, a northern Nguni chiefdom settled on the northern banks of the Tugela river. He embarked on a wave of military conquests over neighbouring Nguni units. The subject chiefdoms were left largely intact, with Dingiswayo as paramount chief over them. The chiefdoms however supplied men for a united army which was controlled directly by Dingiswayo. One such



chiefdom was that of the Zulu, under Senzangakhona, who died in 1816. With Dingiswayo's help, Shaka then seized the Zulu chieftainship and he immediately began expanding his military prowess.

After the defeat of the Mthethwa by Zwide's Ndwandwe in 1817 and the execution of Dingiswayo, Shaka took over the Mthethwa chiefdom. Zwide continued north-westwards and attacked Matiwane's Ngwane, who resided 'around the source of the Black Mfolozi'<sup>6</sup> 'in a triangle between the upper Pongola and Buffels rivers'.<sup>7</sup> However Zwide was soon chased out of the Pongola area by Sobhuza I, chief of the Dlamini, who were lucky to survive vicious retaliatory attacks, by retreating to defensible positions in the Lebombo mountains. Zwide was eventually defeated by Shaka in 1819 - the Ndwandwe fled northwards across the Limpopo where Zwide's sons established the Ngoni and Shangaan chiefdoms. Having defeated Zwide Shaka became ruler over 'a large area extending from the Tugela in the south to the Pongola in the north and from the Buffalo to the sea'.<sup>8</sup>

Matiwane, defeated by Zwide, fled south-westwards, defeated the Hlubi, a 'tekelised' Nguni unit, driving them across the Drakensberg onto the southern highveld. Matiwane, in turn was attacked by Shaka in 1822 and he fled across the Drakensberg in the wake of the Hlubi. This marked the beginning of the Difaqane on the highveld.

Having crossed over the Drakensberg, the Hlubi and later the Ngwane found themselves in Tlokwa country. The next two years witnessed bitter bloodshed and the destruction of many Sotho-Tswana chiefdoms as the Tlokwa under MaNthatisi, the Hlubi under Mapangazita and Matiwane's Ngwane, roamed the southern highveld on a warpath of aggression and destruction. The Hlubi and Ngwane often crossed each others' paths and had old scores to settle. After a number of fierce encounters Matiwane eventually defeated and killed Mapangazita in 1825.

Along the coastal belt Shaka continued his domination of Nguni chiefdoms, driving numerous splinter-groups across the Drakensberg; notably, the Khumalo, under Mzilikatzi, whose father Mashobane had pledged allegiance to Zwide. However in 1818 Zwide killed Mashobane and Mzilikatzi transferred his allegiance from Zwide to Shaka, who allowed Mzilikatzi to maintain his own chiefdom. In 1823 Mzilikatzi defied Shaka and fled with his Khumalo over the Drakensberg, further north across the Vaal, through Transvaal Ndebele country (or Southern Ndebele) and eventually settled in the central Transvaal. The Sotho-speakers occupying the region were either driven off or absorbed into Mzilikatzi's kingdom, giving birth to the Khumalo Ndebele nation, who acquired characteristic features of Zulu tradition (the name 'Ndebele' derives from a Sotho term for Nguni people). From here Mzilikatzi built up his kingdom over the next decade, with vicious attacks and counter-attacks in all directions covering vast distances, northwards across the Limpopo into Shona country, westwards as far as the Molopo river into Tswana country, southwards across the Vaal into Sotho country and eastwards to the Crocodile river in Pedi country.

The Pedi, under chief Thulare of Hurutshe lineage, a Sotho-speaking group lived in the Lulu mountains in the eastern Transvaal. During the Difaqane, Thulare's son, Sekwati, was attacked by Mzilikatzi, Soshangane and Sobhuza, thus driving the Pedi northwards into the Soutpansberg - in 1829 they returned to the Lulu mountains and eventually became the bulk of the North Sotho nation.

Further south between the Great Usutu and the Pongola rivers, which marked the northern boundary of Shaka's kingdom, the Dlamini Ngwane, under Sobhuza I absorbed Sotho and Nguni chiefdoms and laid the foundations of what later became known as the Swazi kingdom (named after Sob-

huza's son, Mswazi). They provided a buffer of resistance against Shaka, by retreating to defensible positions in the southern Lebombo mountains, thus protecting further northern chiefdoms from the direct effects of the Difaqane wars. However, as noted previously, the Pedi living in the eastern Transvaal were attacked from the south-west by Mzilikatzi, driving them northwards into the Soutpansberg for shelter.

The Venda, who had settled north of the Soutpansberg 'around the turn of the eighteenth century'<sup>9</sup> or 'two centuries earlier',<sup>10</sup> were largely unaffected by the Difaqane. They spoke a language very similar to Shona (spoken over the greater part of Zimbabwe) as distinct from Nguni or Sotho-Tswana. Although insignificant in numbers, the Venda provided a trading link between south and north. They were an extremely mystical group of people and, like the Shona and Sotho, they worked in iron, copper and gold and practised masonry construction.

On the southern highveld the devastation caused by the Tlokwa, the Hlubi and the Ngwane, resulted in a wide dispersion of Sotho-speakers in congeries of chiefdoms, until Moshweshwe I consolidated the South Sotho nation in about 1830. After defeating Mapangazita in 1825, Matiwane began threatening Moshweshwe, who summoned Shaka's aid. Matiwane was mauled by Shaka's impis in 1827 and soon thereafter by Mzilikatzi. He then attacked Moshweshwe who also defeated him. Retreating southwards across the Drakensberg, Matiwane started to threaten the Southern Nguni, causing Xhosa and Thembu refugees to flee across the Bushman's river into the Cape Colony. This alarmed the Colonial authorities who believed that it was Shaka's impis embarking on a warpath leading southwards. In 1828 Colonel Henry Somerset was sent to deal with Shaka. With the aid of the Xhosa and Thembu, Somerset defeated Matiwane (still believing it was Shaka), who fled northwards and sought refuge with Shaka. However

Dingane, who had by then seized the Zulu chieftainship, had Matiwane put to death.

After the Difaqane, the fate of practically all the black kingdoms of southern Africa was similar: defeat and domination by the whites, both by the Voortrekkers, who began their Great Trek in 1836, and by the British colonial settlers. The story of the remainder of the nineteenth century is thus largely characterised by conflict between Bantu, Boer and Briton.

The Sotho chiefdoms on the southern highveld, weakened by the Difaqane wars, were extremely vulnerable to domination by the Voortrekkers emerging from the south-west. Many Sotho communities attempting to return to their original country after the Difaqane found their lands claimed by the Trekkers. By this time Moshweshwe was rapidly gaining a reputation as a successful survivor amid the ruins of the Difaqane and thus attracted chiefs who sought protection. Moshweshwe's tactics in defence were similar to those employed by Sobhuza - he retreated into the mountains, positioned his camps on steeply sloping ground and rolled boulders down the slopes of his retreat to drive off his enemies. From his base at Thaba Bosui, Moshweshwe built up a huge empire around the Caledon river valley giving rise to the South Sotho nation.

Mzilikatzi's stronghold in the Transvaal was frequently challenged from the south by Zulu impis and coloured commandos. He thus became suspicious of the Voortrekkers emerging from the same direction, and in 1836 he successively attacked an elephant-hunting expedition, a Voortrekker family, and later the 'laager' of Andries Hendrik Potgieter. Such blood-baths could not be tolerated by the Voortrekkers and revenge was bitter. In 1837 Potgieter and Gert Maritz defeated Mzilikatzi who fled across the Vaal to his original stronghold. There he was again beaten by the Voor-

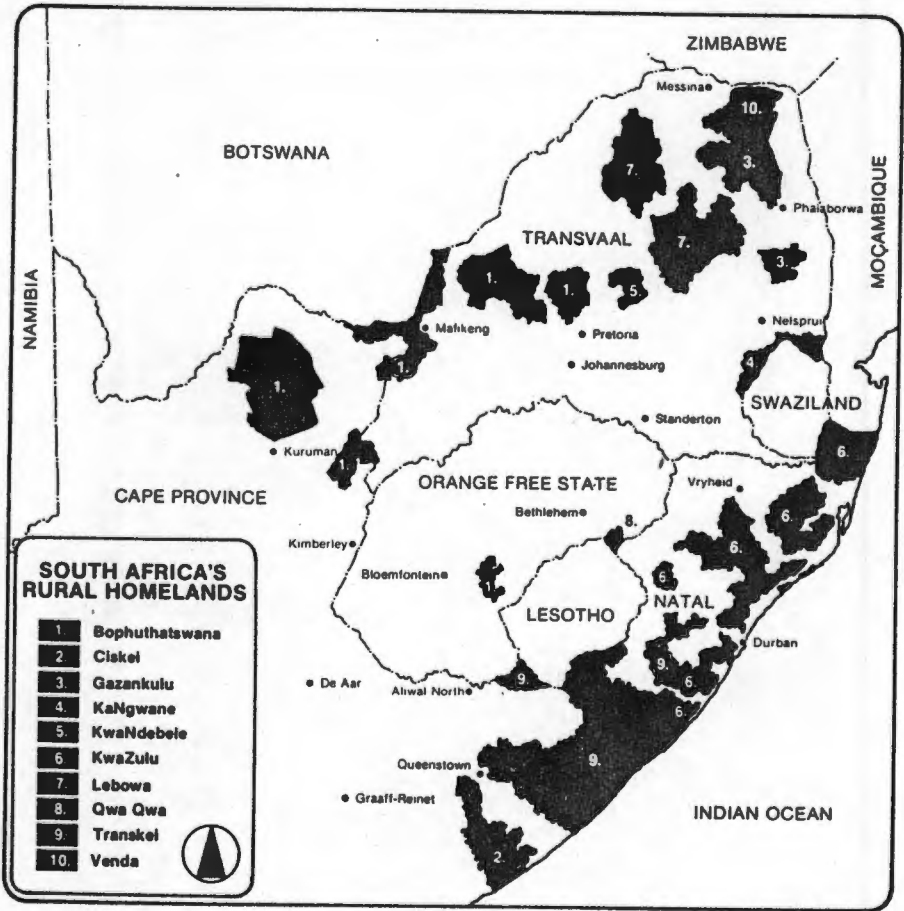
trekkers under Potgieter and Piet Uys, who drove him across the Limpopo into Shona country, where he built his new capital Bulawayo and carved out a new 'Matabeleland', driving off or absorbing the Shona inhabitants.

The post-Difaqane years also saw increasing white domination over the Zulus in Natal. After the murder of Shaka in 1828, the trekboers and British settlers attempted to negotiate peacefully with Dingane. However suspicion and mistrust eventually led Dingane headlong to destruction at the hands of the Voortrekkers. Soon after Dingane had had Piet Retief and his band of Voortrekkers brutally murdered, Andries Pretorius was summoned to rejuvenate the Voortrekkers in Natal. In December of the same year, 1838, Pretorius, with the aid of Dingane's half-brother Mpande, utterly defeated Dingane and drove him northwards towards the Pongola river where he was eventually captured and killed by a Swazi in 1840.

For the next two-and-a-half decades the core of black resistance to white expansion was Moshweshwe's South Sotho kingdom. In 1853 Moshweshwe eventually defeated his major enemy Sekonyela, chief of the Tlokwa, whose vast chieftom was absorbed into Moshweshwe's kingdom. However by 1865 Moshweshwe's resistance to white expansion had become extremely tenuous and the following two years witnessed the crushing defeat of the South Sotho by the Voortrekkers. This massacre was stopped by Sir Philip Wodehouse, British High Commissioner in Natal, who cut off the Voortrekker's ammunition supply.

By 1870 the Sotho were recuperating, but the white settlers took over the administration of their land. Thus the black resistance in southern Africa had finally been defeated - white conquest was followed by the introduction of the white man's title over conquered land and a white ruling government. Western culture and technology became increasingly overpowering and traditional black house forms increasingly bastardised.

|   |                |             |
|---|----------------|-------------|
| A | Lesotho        | South Sotho |
| B | Qwa Qwa        | South Sotho |
| C | Lebowa         | North Sotho |
| D | Bophuthatswana | Tswana      |
| E | KwaNdebele     | Ndebele     |
| F | KaNgwane       | Ngwane      |
| G | Swaziland      | Swazi       |
| H | Gazankulu      | Tsonga      |
| I | Venda          | Venda       |
| J | KwaZulu        | Zulu        |
| K | Transkei       | Xhosa       |
| L | Ciskei         | Xhosa       |



Map of South Africa's major areas of Black rural settlement.

SOURCE : F. Frescura, Rural Shelter in Southern Africa, p.4.



Appendix A : References

- 1 Morris, J.,        Abantu, Struik publishers; Cape Town, 1979, pp. 7-8.  
West, M.,
- 2 Wilson, M.,        A History of South Africa to 1870, David Philip  
Thompson, L.,       press, Cape Town, 1982, p. 90.
- 3 Ibid.,            pp. 87, 195.
- 4 Ibid.,            p. 93.
- 5 Ibid.,            p. 234.
- 6 Ibid.,            p. 393.
- 7 Ibid.,            p. 347.
- 8 Ibid.,            p. 344.
- 9 Ibid.,            p. 98.

## APPENDIX B

### Supplement to Section B (Chapters 3,4,5,6 and 7)

#### B. GEODESIC MATHS : 'ENERGETIC GEOMETRY'

##### B.1 A Brief Introduction to Richard Buckminster Fuller's Philosophy

To summarise Fuller's philosophy is a daunting task. One cannot profess to understand the full extent of his extraordinary way of thinking, and it seems almost impossible to explain his philosophy in abridged form.

"To Fuller what matters fundamentally with regard to both scientific method and social usefulness, is the total physico-economic picture, the Gestalt of nature - the patterns that are inherently comprehensive and universal in contradistinction to what is local." (1)

Like Einstein, Newton, Pythagoras and others, Fuller determined to develop generalised principles which would hold true in every possible instance. He concerned himself with structural design principles based on the universal scientific principles of nature, which he believed inherently lay behind the most efficient structuring possible. Thus, from an early age, Fuller determined to discover the universal co-ordinate system employed by nature and to apply his discoveries and experience in the construction industry, which he believed was technologically lagging behind all other industries. Scientific principles were being applied in the design of ships, airplanes, space capsules and weaponry, but not in the

design of 'livingry' - man's concern with designing a highly technological autonomous dwelling was of minor priority (see Chapter 3). Fuller saw that nature always arranges herself in a rational manner with certain recognisable universal patterns of energy relationships. These regular behaviour patterns can be translated into energy vectors, plotted and measured, and transformed into usable form by developing conceptual universal geometric principles of structure. The regular integrated universal behaviour patterns of nature Fuller refers to as Synergy, which is defined as 'the behaviour of whole systems, unpredicted by the behaviour of their parts taken separately'.<sup>2</sup>

Fuller found that 'structures are not things. Structures are event constellations . . . even the components of atoms are really very remote from one another'.<sup>3</sup> Thus all volumetric quanta or structural systems in nature, from the atom to the Universe, consist of separately islanded compressional 'energy points', which are tensionally cohered. This structural tensional coherence of nature is synergetic, because when a tensile component is tensionally-loaded, its atoms are brought closer together, thus increasing their attraction in terms of the second power of their relative proximity, in accordance with Newton's law of gravity.

Similarly, the synergetic tensional behaviour of alloyed elements, such as chrome-nickel steel, is a result of various atoms complementing each other in such a manner that their islanded energy points are brought closer together, thus increasing their tensional attraction in terms of a second-power progression. This phenomenon is visually demonstrated by the 'dual' polyhedra (see B.3) and explains why the strength of geodesic domes increases at higher frequencies of modular subdivision.

Thus when a tensional member is lengthened, its cross-sectional area can be proportionately decreased - this increasingly favourable slenderness ratio is employed by nature when she has to perform very great tasks, such as cohering the Universe, which is achieved by invisible tensional forces, resulting in such phenomena as gravity and tides.

Fuller expressed concern that man in his everyday social world was unaware of the 'regenerative' benefits which could be derived from synergy; energy in its local context was carefully analysed and behaviour-patterns which could not be predicted by statistical probabilities were ascribed to irrational behaviour, miracle or luck. Thus man developed irrational constants, such as pi, to bridge gaps which seemed illogical to him within the parameters of his thinking process. Due to over-specialisation, this stunted thinking process was further limited to specific fields of work. Biologists, physicists, chemists, mathematicians and architects all pursued their own field of science, gaining experience and knowledge within very limited and specific parameters. However universal scientific principles showed a finite set of variable factors that uniquely govern each system of design science.

"Advancing science has now discovered that all the known cases of biological extinction have been caused by overspecialisation, whose concentration of only selected genes sacrifices general adaptability." (4)

The pool of wealth from which experimentally-based discoveries or knowledge can be derived constitutes the consciously perceived and communicated experiences of all mankind. Only by re-examining and reconsidering these experiences is it possible to develop generalised principles of design science.

"Man's survival is a technological, not a political problem. Abundance is a function of production, not protocol; and man's chances of transforming a disease-ridden, famine-threatened society into a realm of orchestrated abundance depends on his ability to set in order the facts of his experience. Such an order requires a 'comprehensive, anticipatory design science'." (5)

Experience and derived wealth is inherently limited and finite, as the dictionary is limited to a finite set of words. Within the subjective parameters of experience, knowledge and intuition, man has the ability to conceptualise. The imagination can conceive not only the physical or visible, but also the metaphysical or invisible - thus conceptuality is physically independent of size, but being limited to subjective parameters of experience and intuition, it is finite. Similarly, form or structure, both physical and metaphysical, is conceptual and independent of size, because structural arrangements always remain constant and finite. The only variables in all design are the modifications of angle and frequency - an angle is an angle, independent of the size of a particular structural arrangement, and is thus conceptual and generalised. However frequency is a special-case conceptual experience.

In nature the 92 self-regenerative chemical elements have unique frequencies - they constitute the constant and generalised principles of nature. The icosahedron is a structural system which closely follows the example of nature, having 92 equi-radius spheres in the third layer of a closest-packed spherical agglomeration around a 'compressed' nuclear sphere - thus a three-frequency subdivision of the principle icosahedron has 92 vertexes which define the centres of the spheres. (See B.2)

"Fuller regards no single dome of any generic importance; each is to him no more than a local application of a comprehensive system which he calls Energetic Geometry." (6)

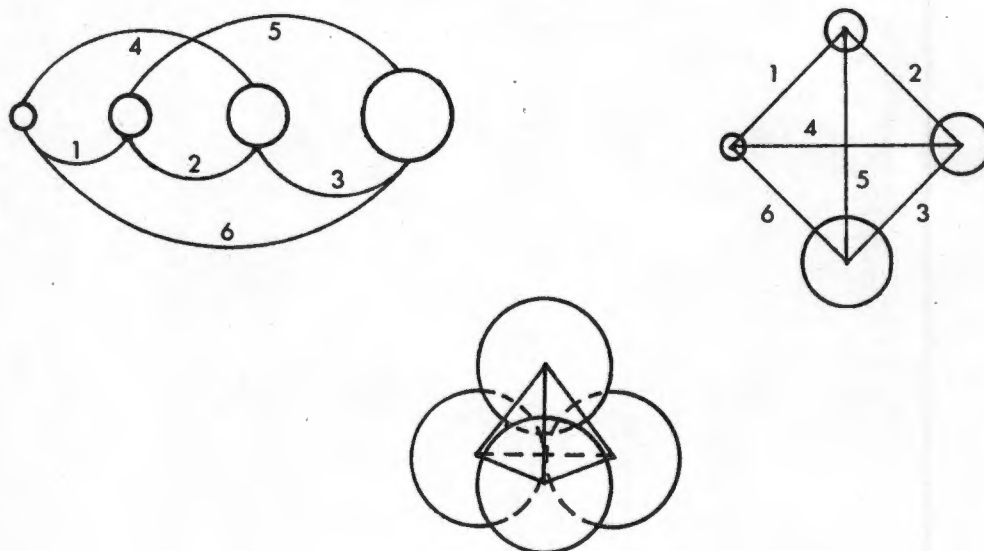
A detailed analysis of Energetic Geometry or Synergetics is beyond the scope of this study, because of the highly intricate philosophical, scientific and mathematical nature of the concept. However it is impossible to ignore a concept which essentially determines the stress patterns of all geodesic domes. The essence of Energetic Geometry is 'the development of mathematical statements for what Fuller calls "the most economical relationship of points in universe and their transformation tendencies"'.<sup>7</sup> The geodesic dome has its structural members intersecting 'at points which are the mathematically determined centres of equal stress lines on the surface of a sphere'.<sup>8</sup> The dome is thus the physical realisation of a conceptual system known as Energetic Geometry.

## B.2 The Closest-packing of Spheres

In his search for nature's universal co-ordinate system, Fuller analysed the concept of closest-packed spheres. He found that the omni-directional closest-packing of equi-radius spheres around a central void results in four spheres all tangent to each other defining the tetrahedron, with the vertexes of the polyhedron being the nuclear centres of the four spheres. Each vector leading from one nuclear centre to another defines one of the six edges of the tetrahedron - each edge is composed of two halves, each half belonging respectively to the two nuclear centres. The vector constitutes a straight line because each half represents that unique radius of each tangent sphere which is perpendicular to the point of tangency.



Figure B.1 Four closest-packed spheres defining the Tetrahedron



The tetrahedron is considered to define structural and volumetric unity with all other structuring being a complex of tetrahedral transformations. In nature, even the microbiological structures, the radiolaria, are based on the tetrahedron.

"The tetrahedron is minimum-prime divisor of omnidirectional universe into two fundamental domains - the withinness and the withoutness, the included and excluded, the microcosm and macrocosm." (9)

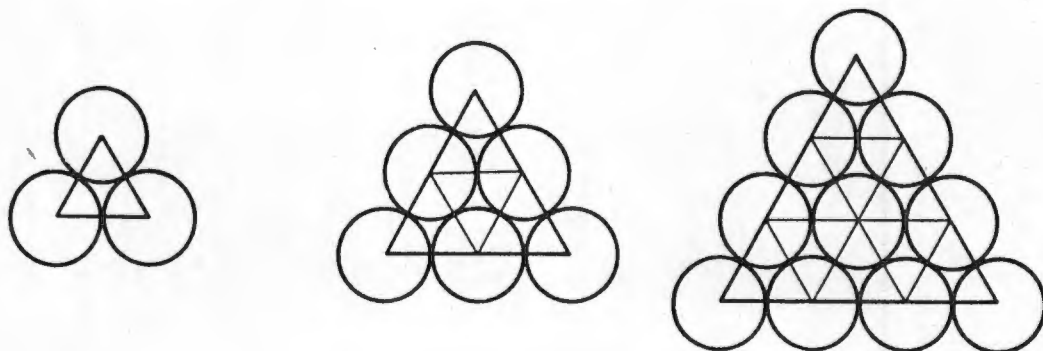
The most basic 'closest-packed array' of four spheres may be surrounded by another shell or layer of equi-radius spheres, resulting in the subdivision of each principle triangular face of the tetrahedron. As more spheres are closest-packed in complete concentric layers, so the edge-frequency of subdivision increases. Thus the edge-frequency may be regarded as the number of layers or the number of edge modules of the tetrahedron - it is the number of spaces between the spheres and not the number of spheres in the outer layer edge.

**Figure B.2** Frequency of subdivision of edges of ONE triangular principal facet of the Tetrahedron

1 layer (0 frequency)

2 layers (2 frequency)

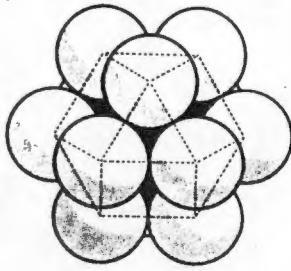
3 layers (3 frequency)



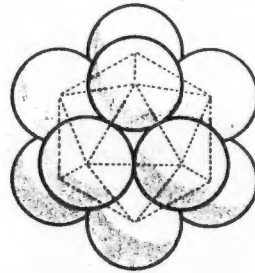
Instead of packing equi-radius spheres around a central void, a central nuclear sphere may be introduced. The first omnidirectional layer of spheres closest-packed around the central sphere constitutes exactly twelve tangentially-packed spheres. The vectors connecting the centres of adjacent spheres define the principal edges of a polyhedron called the cuboctahedron or, as Fuller calls it, the Vector Equilibrium, with eight triangular facets and six square facets. All the circumferential vectors are of equal magnitude as well as being equal to the radial vectors from the centre of the polyhedron to its twenty vertexes - hence the name Vector Equilibrium or Isotropic Vector Matrix. The second layer contains 42 closest-packed spheres, the third has 92 spheres, a number analogous with the 92 'unique regenerative atomic systems' or chemical elements in nature.<sup>10</sup>

If the nuclear sphere is removed or compressed, the remaining twelve first-layer spheres close in to define a polyhedron with twenty triangular facets, the icosahedron. It is thus evident that the vector equilibrium and the icosahedron are close relatives, both having the same number of vertexes or surface-defining spheres in each shell.

Figure B.3 Vector Equilibrium and Icosahedron



**A**  
Vector Equilibrium  
spheres closest-packed  
around a nuclear sphere



**B**  
Icosahedron  
nuclear sphere removed  
or compressed

**NOTE:** A contracts symmetrically to become a more compact arrangement, B.

The number of spheres in each concentric layer of any omnitriangulated structural system, or stabilised polyhedron, can be calculated by means of the following formula:

$$X = 2NF^2 + 2$$

Where

X = number of spheres in the outer shell

N = one of the first four prime numbers:

- 1 if the structural system is tetrahedral,
- 2 if it is octahedral,
- 3 if it is the triangularly structured cube,
- 5 if it is the icosahedron or the triangularly stabilised vector equilibrium

F = edge frequency i.e. the number of outer layer edge modules<sup>11</sup>

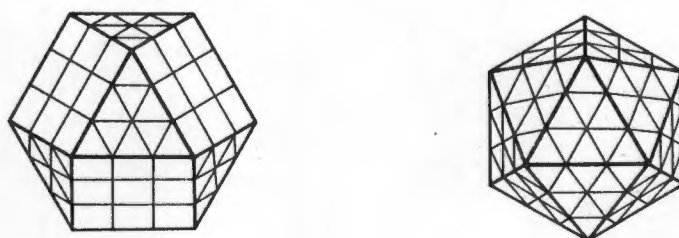
The additive twoness derives from the polar vertexes of the neutral axis of spin of all systems (see B.4). The multiplicative twoness characterises the coexistent insideness and outsideness of all polyhedra i.e. each polyhedron has two faces: obverse and reverse.

"The number of vertexes of the omnitriangulated spherical tetra-, octa-, or icosahedral structures of multifrequency geodesicspheres corresponds exactly with the number of external layer spheres of closest-packed unit radius spherical agglomeration of tetrahedra, octahedra or icosahedra." (12)

Applying the formula to the vector equilibrium and icosahedron, modulated to a 3-frequency subdivision:

$$X = 2 \times 5 \times 3^2 + 2 = 92$$

Figure B.4 3-frequency subdivision of Vector Equilibrium and Icosahedron



Notice again that the icosahedron is a symmetrically contracted, more compact derivative of the vector equilibrium, but both figures have an equal number of vertexes.

### B.3 Elementary Polyhedral Geometry

In order to clearly understand the basic designs of geodesic domes, one must recall the elementary study of polyhedral geometry, a conceptual geometry which inherently subdivides the Universe into distinctly separate microcosms and macrocosms, defining concave inwardness and convex outwardness respectively.

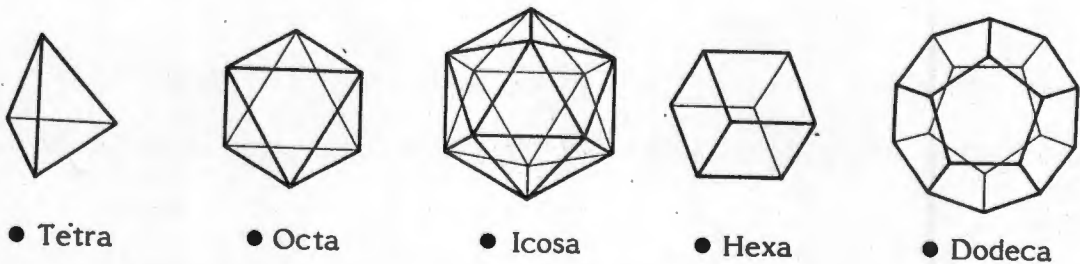
A polyhedron is defined by a set of polygons arranged in space in such a way that every side of a polygon belongs to only one other polygon; the polygons, their sides and apexes are called the faces, edges and vertexes (or openings, trajectories and crossings as they are known in Synergetics) of the polyhedron. The basic three-dimensional form of a polyhedron therefore comprises two-dimensional faces, one-dimensional edges and zero-dimensional vertexes, with faces joining each other along edges,

which meet at vertexes, which are points on the surface of a common circumscribed sphere.

The most basic structures known in nature are called the 'Platonic solids'. Polyhedra based on platonic structuring thus define the simplest method of creating regular, symmetrical space-enclosing structures. Platonic polyhedra must by definition have equal faces, equal angles between adjacent faces and equal vertexes. There are only three equilateral polygons which will fit together in three-dimensional space to define the five platonic polyhedra:

- The equilateral triangle, which combines to form the tetrahedron, the octahedron and the icosahedron, by having three, four and five triangles respectively around each vertex.
- The square, which combines in threes at each vertex to form the cube (or hexahedron).
- The regular pentagon, which combines in threes at each vertex to form the dodecahedron.

Figure B.5    Platonic Polyhedra



Of the five platonic polyhedra, the cube has become the most common archetype for construction. It is however clearly evident that when struts defining the edges of a cube (as well as the dodecahedron) are joined with flexible connectors the resultant structure is unstable, whereas the tetrahedron, the octahedron and the icosahedron are perfectly sta-

ble due to their basic triangular subdivision.

"Only tetrahedral, octahedral and icosahedral structural systems are stable i.e. complete non-redundant, self-stabilising." (13)

The development of geodesic domes is therefore confined to those polyhedra which are inherently stable; furthermore, the icosahedron, being the polyhedron which most closely approximates a sphere, is the basic form from which most geodesic domes are generated. Of the three fundamental stable structures, the tetrahedron contains the least volume with the most surface area and is therefore the strongest structure per unit of volume; whereas, the icosahedron gives the most volume with the least surface area and though least strong, it is stable and most economical in terms of invested material.

Table B.1 shows the relation of 'platonic' polyhedra in terms of the number of faces, edges and vertexes.

Table B.1

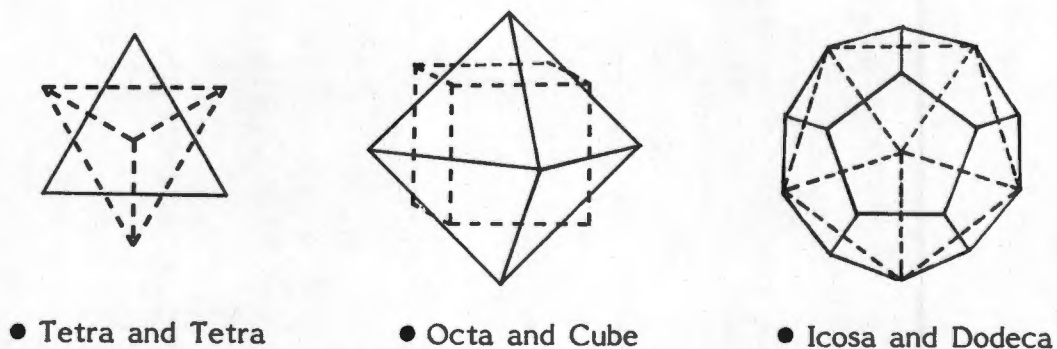
|   | Polyhedron   | No. of Faces | No. of Edges | No. of Vertexes |
|---|--------------|--------------|--------------|-----------------|
| 1 | Tetrahedron  | 4            | 6            | 4               |
| 2 | Cube         | 6            | 12           | 8               |
| 3 | Octahedron   | 8            | 12           | 6               |
| 4 | Dodecahedron | 12           | 30           | 20              |
| 5 | Icosahedron  | 20           | 30           | 12              |

Any two of these polyhedra which have an equal number of edges, with the one polyhedron having as many vertexes as the other has faces, share a relationship called 'duality'. Thus the cube and the octahedron are duals, as are the icosahedron and the dodecahedron; the tetrahedron is



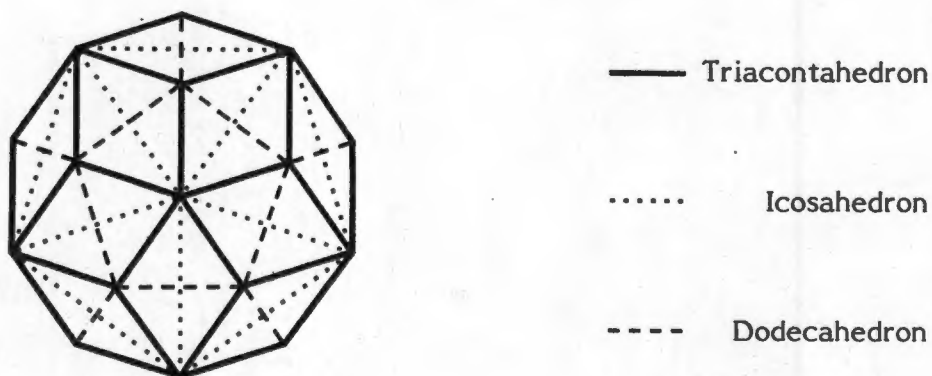
its own dual. The dual of any polyhedron is derived by inscribing a sphere so that it is tangent to the midpoints of the polyhedron's edges and then by drawing lines perpendicular to the edges and tangent to the sphere at those points.

Figure B.6 'Dual' Polyhedra



Taking the icosahedron and dodecahedron and connecting their vertexes, a new polyhedron with thirty diamond-shaped faces is formed - this is the triacontahedron.

Figure B.7 Triacontahedron

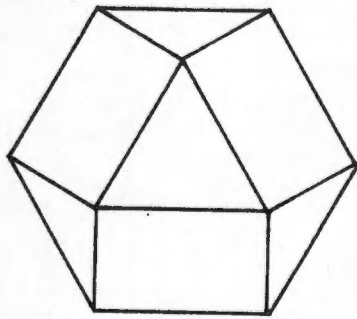


The edges of the dodecahedron and the triacontahedron define a 2-frequency triacon dome (see B.6.2).

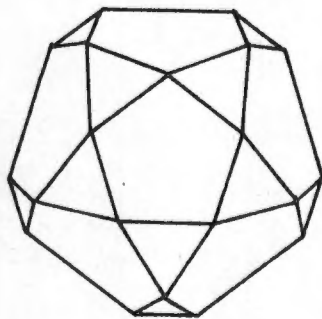
More interesting shapes can be achieved from these dual pairs. By trim-

ming the corners off the cube and octahedron combination, the cuboctahedron is formed. Similarly the isidodecahedron is formed by slicing the corners off the icosadodeca combination - this forms the basis of a 2-frequency alternate dome. The pentagonal and hexagonal skeleton of a 3-frequency alternate dome is formed by trimming the corners of the icosahedron, resulting in the truncated icosahedron.

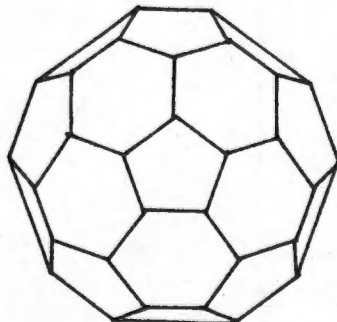
Figure B.8 Cuboctahedron, Isidodecahedron, Truncated Icosahedron



Cuboctahedron



Isidodecahedron



Truncated  
Icosahedron

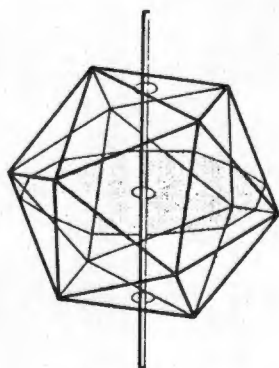
#### B.4 Great Circles of the Icosahedron

'Great circles' are the largest circles that can be drawn upon the surface of a sphere. They define the circumference of a sphere at its diameter thus cutting the sphere exactly in half. The term used by mathematicians to describe these curves is geodesic, which comes from the Greek for 'earth-dividing'.

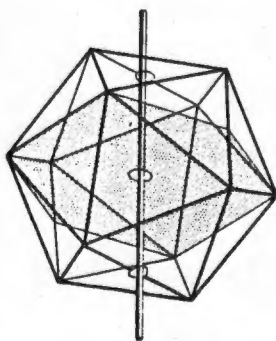
The essence of geodesic structuring is the 'explosion' or projection of the principal polyhedron onto the surface of a sphere; then the points of intersection of a three-way grid of great circles, which subdivide the triangular facets of the polyhedron, are determined. The icosahedron has the highest number of identical and symmetrical triangular facets of all great circle-defined polyhedra, with twenty faces, twelve vertexes and thirty edges. Thus most geodesic domes are derived from the icosahedron, which has three unique symmetric sets of axes of spin:

- 1 through the centres of opposite faces
- 2 through the midpoints of opposite edges
- 3 through opposite vertexes.

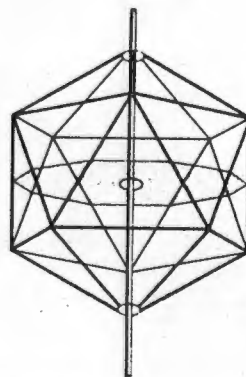
Figure B.9 Icosahedron's Three Unique Axes of Spin



Centre of face  
to centre of  
diagrammatically  
opposite face



Centre of edge  
to centre of  
diagrammatically  
opposite edge



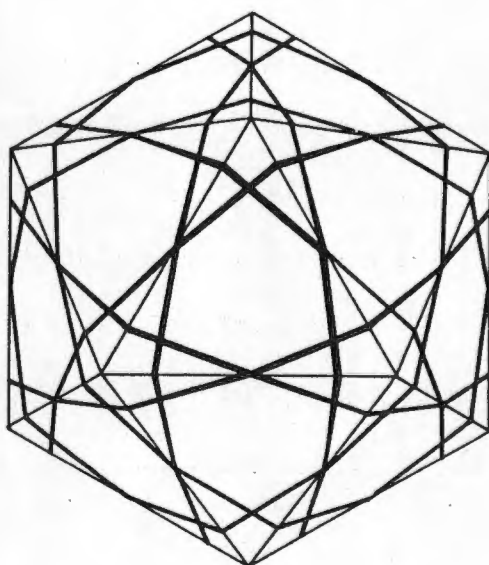
Vertex  
to diagrammatically  
opposite vertex

By rotating the icosahedron on each neutral axis a number of equatorial circular planes are defined with each plane passing through the centre of the polyhedron. These great circle planes define 31 great circle lines, which make-up the three-way geodesic grid. Since they are all maximum bands of length, and stress applied at any particular point is passed throughout the entire band, all structural members (or struts) which are aligned with the lines of the grid, being great circle segment chords, are more uniformly stressed than members of any other form of construction.

**NOTE:** Practical problem: Because domes are only partial spheres, the stress in every band is passed to the cut-off points. Thus secure fixing points are required along the cut-off plane (or base) to prevent tensile 'spreading' of the base members.

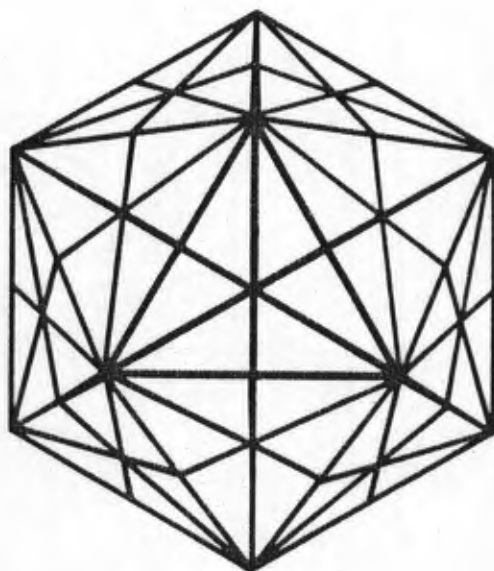
**B.4.1** Rotation of the icosahedron on an axis through the centres of opposite faces, defines TEN great circles.

Figure B.10



B.4.2 Rotation of the icosahedron on an axis through the midpoint of opposite edges, defines FIFTEEN great circles.

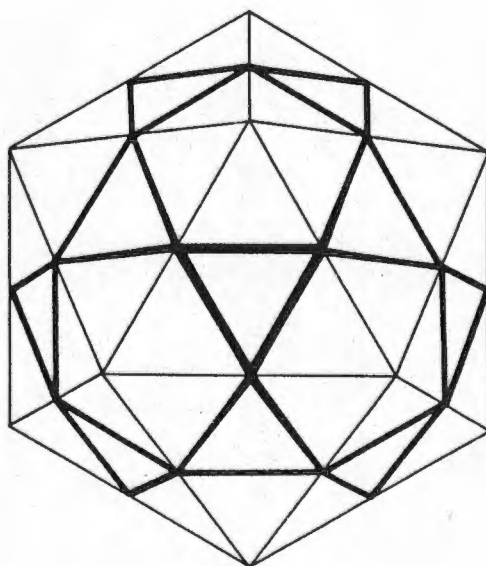
Figure B.11



NOTE: The identical subdivision is achieved by superimposing the icosahedron, the dodecahedron and the rhombic triacontahedron (see B.3)

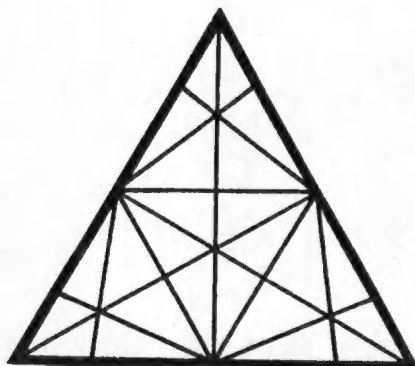
B.4.3 Rotation of the icosahedron on an axis through opposite vertexes, defines SIX great circles.

Figure B.12



B.4.4 Each of the icosahedron's twenty triangular faces is divided by the THIRTY-ONE great circles in a similar way.

Figure B.13



#### B.4.5 Orientation

The orientation in space of a geodesic dome is determined by the orientation of the principal polyhedron, which has either a face or an edge or a vertex at its apex - the dome is consequently termed 'face-zenith' or 'edge-zenith' or 'vertex-zenith' respectively. Unless otherwise stated all domes analysed in the context of this study have a 'vertex-zenith' orientation.

### B.5 Spherical Trigonometry

#### B.5.1 Introduction

The study of great circles presents data from which a dome of any frequency can be derived. However all great circles are not represented in every dome and the struts of a dome do not always coincide with great circle segment chords.

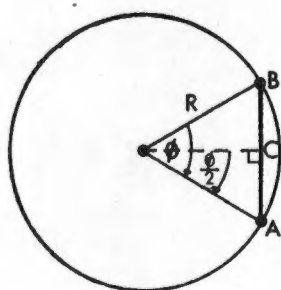
The spherical trigonometry involved in solving great circles is greatly simplified by analysing spherical right-angle triangles rather than oblique



triangles . The angles, as well as all arc lengths, are measured in degrees. Some arcs are portions of complete great circles - thus their length is a portion of 360°. The length of an arc is a function of the size of the sphere and of the angle it subtends at the centre of the sphere (central angle). Because a segment chord subtends the same central angle, it is possible to convert the value from degrees to a chord factor.

NOTE: An arc of  $X^\circ$  subtends a central angle of  $X^\circ$ .

Figure B.14 Derivation of Chord Factor



Assume radius (R) = 1 unit

$$BC = R \sin \frac{\phi}{2} = \sin \frac{\phi}{2}$$

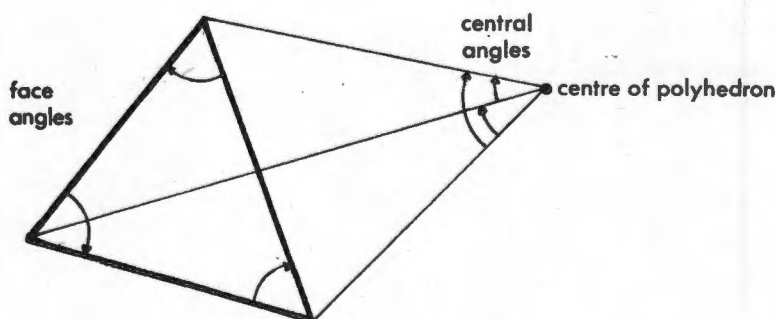
$$AB = 2 \sin \frac{\phi}{2} \text{ (chord factor)}$$

## B.5.2 Angles of the Planar-faceted Icosahedron

### B.5.2.1 Face Angles and Central Angles

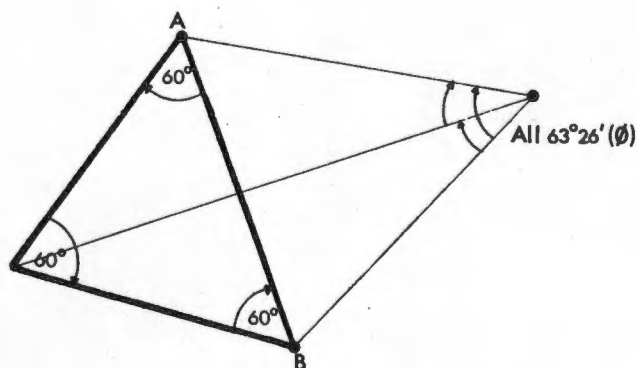
Each equilateral triangular facet of the tetra-, octa-, and icosahedron has three face angles and three central angles.

Figure B.15



Both the tetra and the octa have an edge to radius ratio of 1,000. Thus all face angles and central angles of each triangular facet are  $60^\circ$  and it is possible to close-pack tetras and octas. A two-frequency tetra has each principal tetra facet divided into four smaller equal facets, resulting in an octa being formed inside the principal tetra, with four congruent tetras packed around the octa. As more tetras and octas are close-packed in a plane, the octet-truss is formed, which is the basis of modern space-frame systems. If close-packed spherically the octet-truss appears to form a complete sphere with an icosahedron inside. However it will not close completely because the edge to radius ratio of an icosahedron is 1,0515 not 1,000. This means that each central angle of the icosahedron facets is slightly greater than  $60^\circ$ , being  $63^\circ 26'$  (or  $63,44^\circ$ ). The face angles of each icosahedron facet are all  $60^\circ$ .

Figure B.16



$$AB = 2 \sin \frac{\emptyset}{2} = 1,0515$$

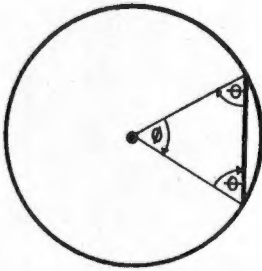
Face Angles are important in dome construction as they are used in hub-designs and to calculate the 'mitre-cuts' at each strut end, as well as determining the angles of the cladding panels (see Chapter 4).

Central Angles are important because they are used to calculate 'chord factors' as well as axial angles.

### B.5.2.2 Axial Angles ( $\theta$ )

Axial angles are a function of the central angle subtended by a chord. They are the angles between strut ends and the radius from the centre of the sphere and are calculated as follows:

Figure B.17



Axial angle ( $\theta$ ) =  $\frac{1}{2}$  (180° minus central angle ( $\phi$ ))

$$\theta = 180^\circ - 2\phi$$

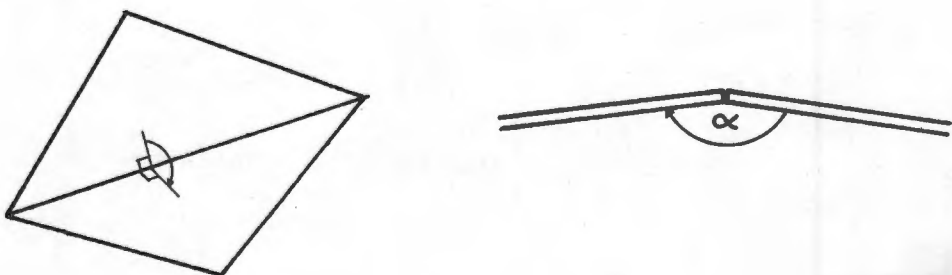
$$\begin{aligned}\theta \text{ of an icosahedron edge} &= \frac{1}{2} (180^\circ - 63,44^\circ) \\ &= 58,28^\circ (58^\circ 17')\end{aligned}$$

Axial Angles are important in dome construction because they are used in hub-designs and in 'splay-cutting' strut ends.

### B.5.2.3 Dihedral Angles ( $\alpha$ )

A dihedral angle is the internal angle between two faces that share a common edge; it is the supplement of the 'breaking angle' between faces. Calculating the angles involves some fairly elaborate trigonometry which, as far as can be ascertained, has only been published in David Kruschke's book 'Dome Cookbook of Geodesic Geometry', which seems to be very difficult to obtain - it was ordered over a year ago, both privately and through a bookshop, but has as yet not arrived.

Figure B.18

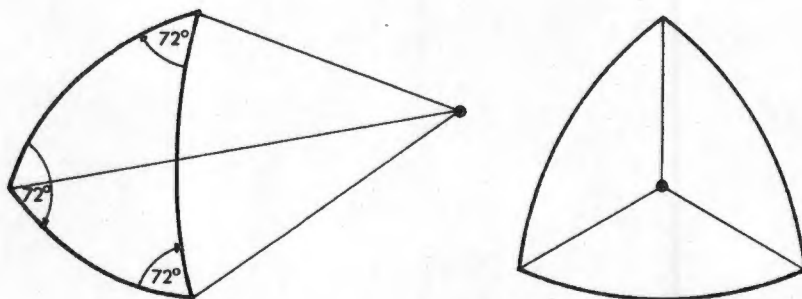


All dihedral angles of the planar icosahedron are  $138,18^\circ$  ( $138^\circ 11'$ ).

Dihedral Angles are important in dome construction, as they determine the 'bevel-cutting' or 'ripping' of struts.

### B.5.3 Face Angles of the Spherical Icosahedron

Figure B.19



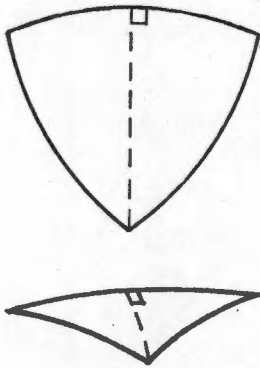
The sum of the angles of a spherical triangle is always less than  $540^\circ$ , but more than  $180^\circ$ . The amount over  $180^\circ$  is called the 'spherical excess'. At any particular point on the surface of a sphere, the spherical excess tends towards  $0^\circ$  - thus the sum of the angles around that point is  $360^\circ$ . The spherical icosahedron has five equal face angles around each vertex - thus each face angle is  $72^\circ$ . Each equiarc triangular face of the icosahedron thus has a spherical excess of  $36^\circ$ . To calculate the planar face angles, the spherical excess for the whole triangle is divided by three and then the result is subtracted from each vertex. This results in each planar equilateral triangular face of the icosahedron having three face angles of  $60^\circ$ .

### B.5.4 Napier's Rule

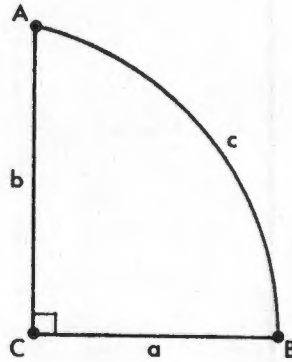
Right-angled spherical triangles are easier to solve than oblique triangles. Any oblique triangle can be converted into two right-angled spherical triangles by dropping a perpendicular from any vertex to the opposite side.

By convention, the two sides of a triangle containing the right angle are represented as being straight lines whilst the third is arcuate.

Figure B.20 Right-angled spherical triangle



Oblique triangles with  
perpendicular to define  
two right-angled triangles



By Convention: Right-  
angled spherical triangle

Any spherical triangle can be solved by means of Napier's Rule, if it has one right-angle and five variables of which two are known.

Napier's Rule:

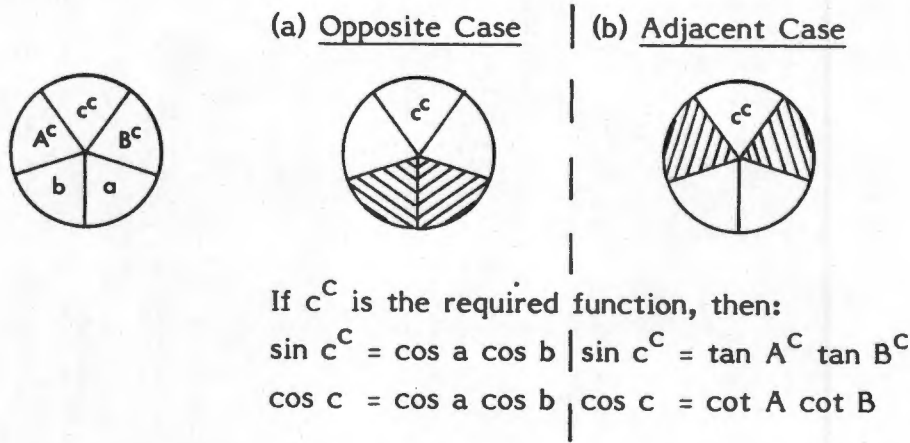
SIN of any variable = product of either:

- (a) COS of opposites, or
- (b) TAN of adjacents

In order to apply the rule, the five variables in a right-angled spherical triangle (the sixth variable, the right-angle, is known and is thus omitted) are graphically represented as shown in Figure B.21.

NOTE: ● The superscript 'c' means the use of complementary functions.  
● The angle 'C' is omitted, as it is known.

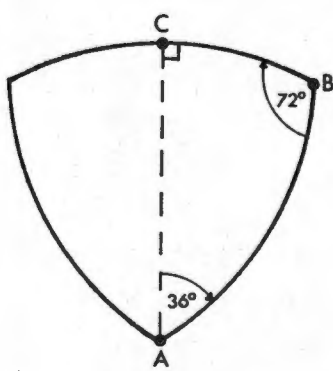
Figure B.21 Napier's Rule



B.5.5 Application of Napier' Rule to solve Great Circles

To solve a spherical triangle by means of Napier's Rule, it must have one right-angle and five variables, of which two are known.

- It has been established that each equiarc triangle of the icosahedron has three face angles of  $72^\circ$ . By dropping a perpendicular from any vertex to the opposite side, the angle at the vertex and the length of the opposite side are both bisected.

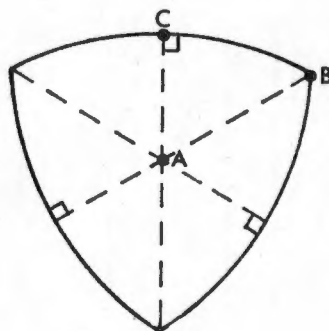


Having established two variables i.e.  $B = 72^\circ$  and  $A = 36^\circ$ , triangle ABC can be solved.

- The 15 great circles, produced by rotating the icosahedron on an axis through the midpoint of opposite edges, divide each face into six identical right-angled spherical triangles by providing the other



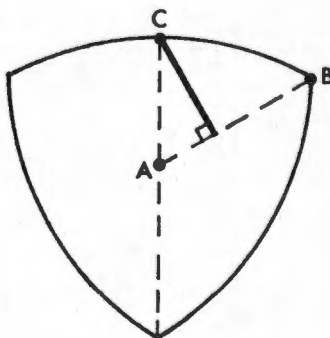
two perpendicular bisectors of the equiarc triangle. The resultant 120 identical right-angled triangles represent the largest equal subdivision of the icosahedron's surface facets. By solving one of the triangles all others can be derived by rotating the solved one.



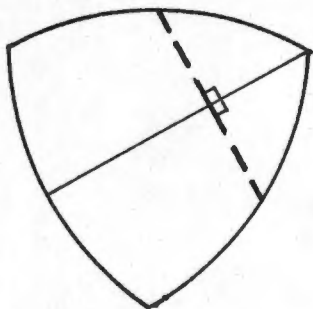
The sum of the angles around a point on the surface of a sphere equals  $360^\circ$  - there are six equal angles at the centre of the face (A), thus each angle equals  $60^\circ$ .

Triangle ABC can be solved and checked, because three variables are known i.e.  $A = 36^\circ$ ,  $B = 60^\circ$  and the length of BC has been solved.

- The next perpendicular is dropped from C to AB.

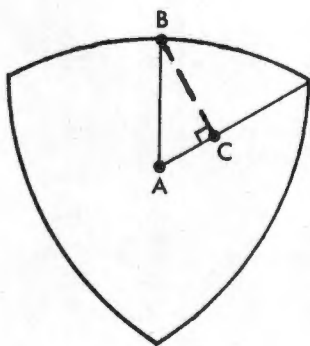


This perpendicular arc constitutes part of one of the 6 great circles, produced by rotating the icosahedron on an axis through opposite vertexes. Each of the 6 great circles crosses ten of the icosahedron's faces. Thus each segment arc is  $1/10$  of the equator or  $36^\circ$ .



Each dotted line is  $1/10$  of the equator, or  $36^\circ$

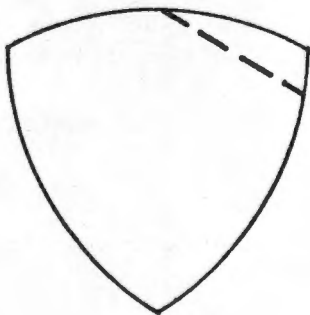
By superimposing the 15 great circles, each  $1/10$  equator segment is bisected perpendicularly - thus the section of the equator passing through a right-angled triangle is  $1/20$  of the whole equator, or  $18^\circ$ .



Each dotted line is  $1/20$  of the equator, or  $18^\circ$

Triangle ABC is a right-angled triangle and can be solved.

- Each of the 10 great circles, produced by rotating the icosahedron through the centres of opposite faces, crosses twelve of the icosahedron's faces. Thus each segment is  $1/12$  of the equator, or  $30^\circ$ .

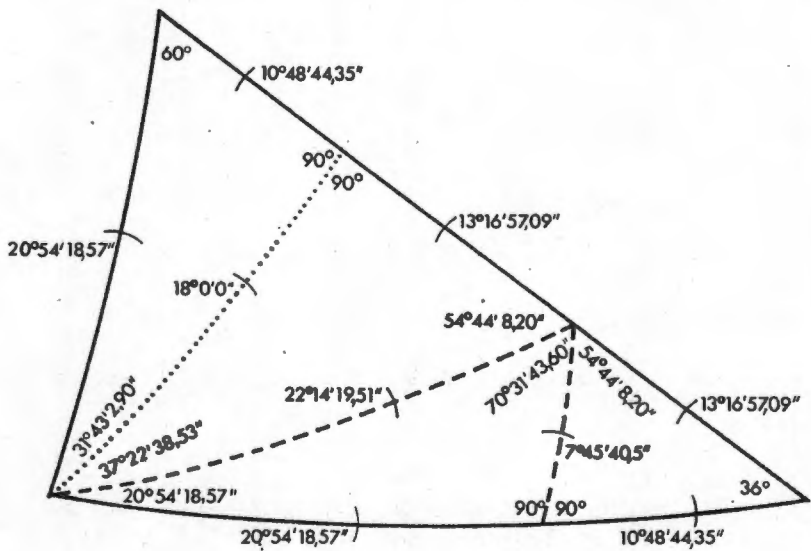


Each dotted line is  $1/12$  of the equator, or  $30^\circ$

By applying Napier's Rule further, all 31 great circles can be solved, thus providing data for domes of any frequency of subdivision. Figure B.22 gives all the required data on the great circle arcs which pass through one of the 120 equal right-angled spherical triangles.

"The Basic Disequilibrium 120 LCD Spherical Triangle and its multifrequenced triangular subdivision is the basis for calculating all high-frequency, triangulated, spherical structures and structural subportions of spheres; for within only one disequilibrium LCD triangle are to be found all the spherical chord-factor constants for any desired radius of omnisubtriangulated spherical structure." (14)

Figure B.22    Angles of LCD Spherical Triangle



## B.6 Geodesic Breakdowns

### B.6.1. Introduction

It was previously stated that each principal icosahedron facet is too large and cumbersome when constructed on the scale of a full-size dwelling unit (see 4.1). Thus each triangular cladding panel would sag in the centre and require internal bracing. The most efficient bracing would be achieved by a triangular subdivision anyway - thus it might as well be used to give the structure a more spherical shape, thereby increasing its overall structural strength. As the frequency of subdivision of the principal icosahedron edges increases, so they become progressively more arcuate until a 16-frequency subdivision is reached, at which stage the edge is assumed to coincide with the arc of a sphere.

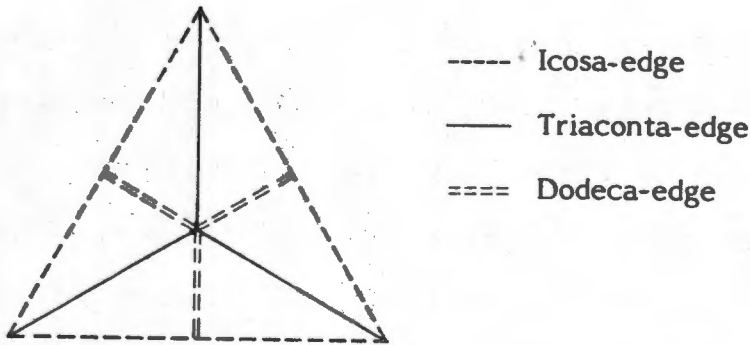
The mathematical details of any frequency subdivision may be calculated either by means of spherical trigonometry or by analytical geometry. Buckminster Fuller developed his geodesic breakdowns by means of calculations using arcs on a sphere. He developed domes by projecting the icosahedron onto a circumscribed sphere and then by dividing the face of the spherical icosahedron with great circle arcs on the surface of the sphere (see B.4). He calculated chord lengths, angles, etc. by means of spherical trigonometry (see B.5). On the other hand, Joe Clinton subdivided the planar icosahedron facets into smaller triangles and then projected the points of subdivision onto the surface of a circumscribed sphere. With the coordinates of these points and analytical geometric formulas he calculated chord lengths, angles, etc. by computer - the results are published in 'Domebook 2' and serve as the basis of most geodesic dome designs.

Although the time-consuming mathematical spadework has been done, it is interesting to analyse the methods used in subdividing the icosahedron's facets.

B.6.2 The 'Triacon' Breakdown

The superimposition of the icosahedron, the dodecahedron and the rhombic triacontahedron results in the same 120 LCD right-angled triangular subdivision of the icosahedron's surface as the 15 great circles do (see Figure B.7 and Figure B.11). This is the basis of a geodesic breakdown known as the Triacon method. The edge of the icosahedron is not part of a dome in the triacon breakdown. The most basic dome framework defines the edges of only the principal dodecahedron and triacontahedron - hence the name 'triacon' (see 6.4). Each imaginary edge of the icosahedron is perpendicularly bisected by an edge of the dodecahedron. Thus the most basic triacon breakdown results in a 2-frequency subdivision of the icosahedron's principal edges and higher subdivisions are only possible in even frequencies.

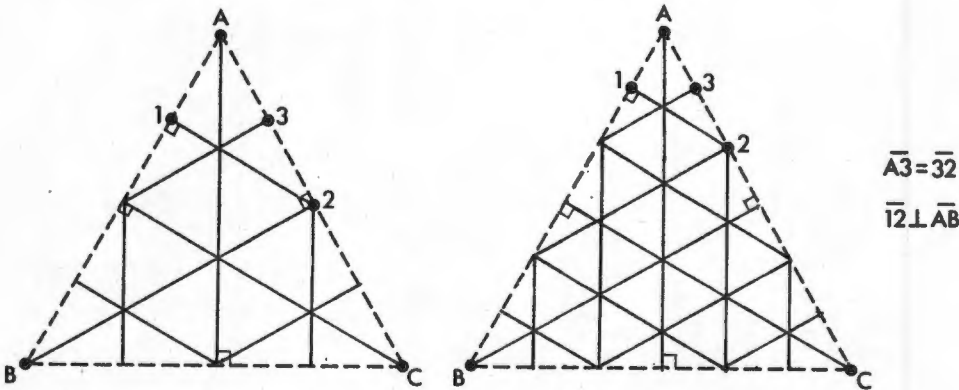
Figure B.23 Triacon Breakdown: 2-frequency subdivision of an icosafacet



Further subdivision may be achieved by various methods of which the following two are most common:

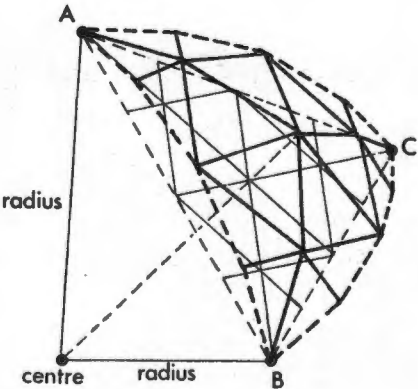
- Each icoso-edge is subdivided into  $n$  frequency, with the parts chosen as equal divisions. Each point of subdivision is then connected with a perpendicular to its side. This has the same effect as drawing a line from each point parallel to the original perpendicular bisector. The three-way grid thus defined comprises equilateral and right-angled triangles.

Figure B.24    Triacon Breakdown: 4- and 6-frequency subdivision of an icoso-facet



Each vertex on the planar icoso-facet is projected onto the surface of the circumscribed sphere along a line passing through the vertex and the centre of the icosahedron. The vertexes are now connected to form the chords of a three-way geodesic grid.

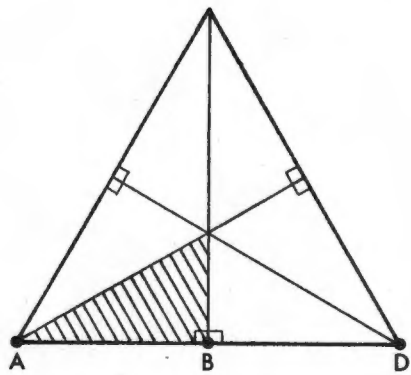
Figure B.25





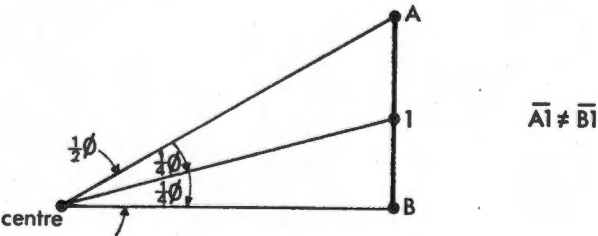
- Each icosafacet contains six LCD equal right-angled triangles - by solving one triangle the others can be derived by rotation.

Figure B.26



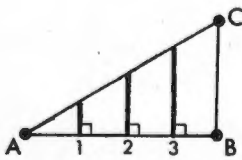
$\overline{AD}$  subtends central angle  $\emptyset$ ; thus  $\overline{AB}$  subtends  $\frac{1}{2} \emptyset$ . To subdivide  $\overline{AB}$ , the line is subdivided into parts chosen as equal arc divisions of the central angle as follows:

Figure B.27

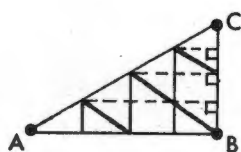


- One  $\frac{1}{2} \emptyset$  gives a 2-frequency subdivision
- Two  $\frac{1}{4} \emptyset$  gives a 4-frequency subdivision
- Three  $\frac{1}{6} \emptyset$  gives a 6-frequency subdivision
- Four  $\frac{1}{8} \emptyset$  gives an 8-frequency subdivision
- etc.

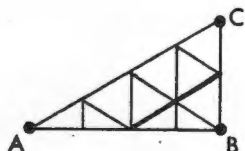
Taking one LCD right-angled triangle,  $\overline{AB}$  is divided into say four  $\frac{1}{8} \emptyset$  subdivisions. The three-way grid is developed as follows:



Perpendicular lines from points of subdivision on  $\overline{AB}$  define points of subdivision on  $\overline{AC}$



From each point on  $\overline{AC}$  extend a line perpendicular to  $\overline{BC}$ . Draw diagonals from each point of  $\overline{AC}$  to alternate points on  $\overline{AB}$  and  $\overline{BC}$ .



From points on  $\overline{BC}$  draw a line to alternate points on  $\overline{AB}$ .

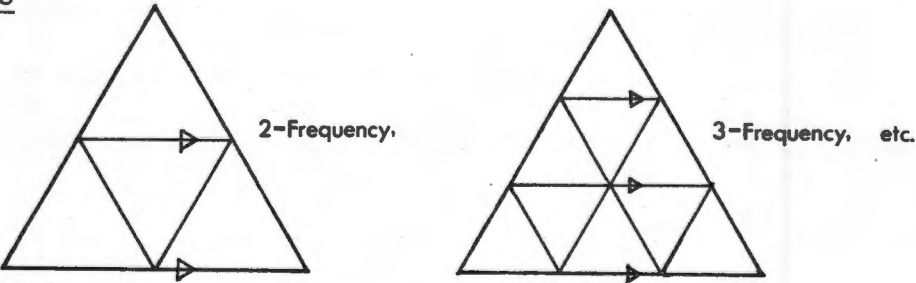
Having completed triangle ABC, it is rotated to derive subdivisions for the entire principal icsa-face. Each vertex is translated onto a sphere as before, and chords define the three-way geodesic grid.

The latter method of achieving a triacon breakdown will not produce the smooth arcs that one gets with the former method; however the number of different strut lengths will be less, especially at higher frequencies. The triangles will be more equilateral, thus the dome is structurally stronger.

B.6.3 The 'Alternate' Breakdown

The second geodesic breakdown or the Alternate breakdown is possible in both even and odd frequencies because line segments are not perpendicular bisectors of each icsa-edge - instead they are parallel.

Figure B.28

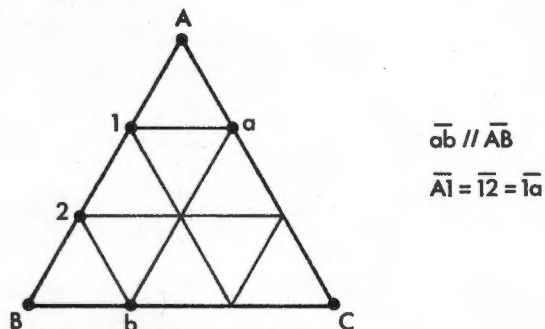


NOTE: The icsa-edges are part of a dome in the alternate breakdown.

The following are the two most common methods of subdivision:

- Each icoso-edge is subdivided into equal divisions of  $n$  frequency - parallel line segments join points of subdivision as above.

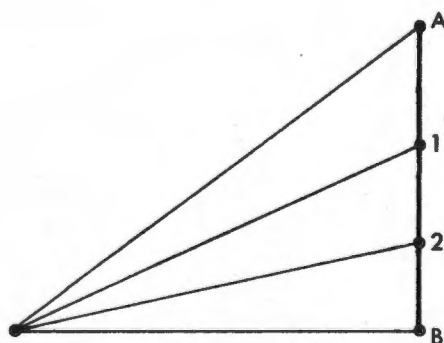
Figure B.29 Alternate Breakdown: 3-frequency subdivision of an icoso facet



Each resultant vertex is projected onto the surface of a circumscribed sphere as before. Adjacent vertexes are connected to form chords of a three-way geodesic grid.

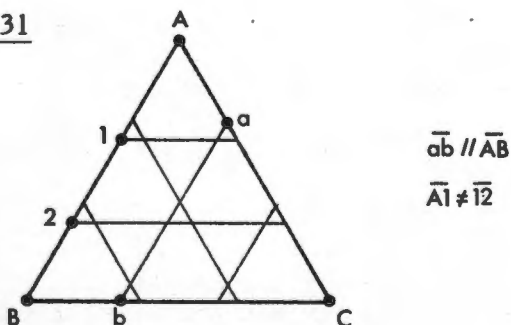
- Each icoso-edge is subdivided into  $n$  frequency with parts chosen as equal arc divisions of the central angle.

Figure B.30



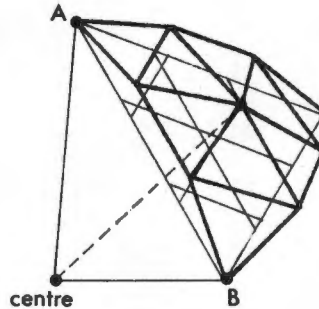
Again parallel line segments join points of subdivision to define a three-way geodesic grid.

Figure B.31



The line segments do not meet at exactly the same point, thus defining small equilateral triangles or 'windows' around the points of subdivision.

Figure B.32



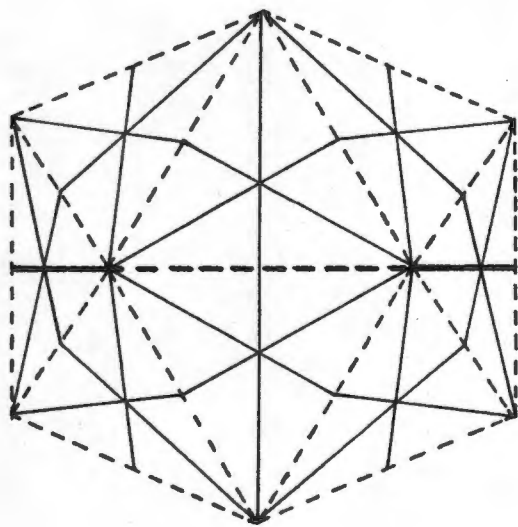
The centres of these 'windows' are used as the vertexes of the three-way grid, which is projected onto the surface of a circumscribed sphere as before.

#### B.6.4 'Triacon' versus 'Alternate'

The 'triacon' breakdown resembles Fuller's original breakdown more closely than the 'alternate' breakdown does. Due to its high symmetry, it requires fewer different strut lengths than Fuller's original breakdown. The purist dome builder will prefer the triacon to the alternate breakdown because its edges are in closer alignment with the great circles produced by rotating the icosahedron on its three axes. All 2-frequency triacon dome edges are aligned with the 15 great circles defined by rotating the icosahedron on an axis through the midpoint of opposite edges. The 2-frequency is the most basic triacon breakdown and all higher frequency subdivisions are even and manifest the basic 2-frequency division. Thus, when any frequency triacon dome is placed in space with an edge-zenith orientation, there is always a complete great circle which divides the

dome into a hemisphere which sits flat on a horizontal base. Struts of the triacon dome are in alignment with this horizontal great circle except where the circle defines two diagrammatically opposite edges of the icosahedron - since the triacon breakdown does not define any icosi-edges, the horizontal great circle will cut some triangles exactly in half.

Figure B.33 Triacon Breakdown: Hemispheric Truncation of Icosahedron

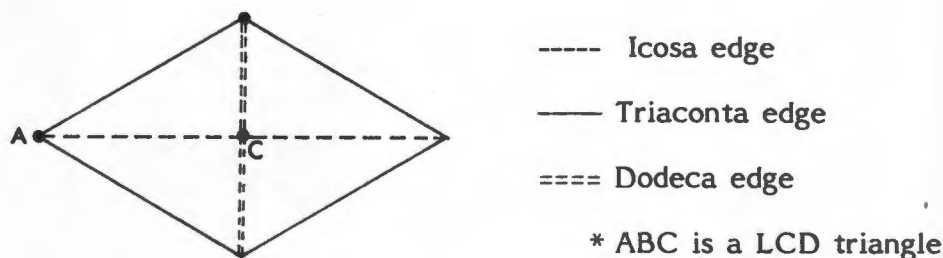


The icosi-edge is part of the horizontal great circle and cuts triangles of a 2-frequency triacon dome in half (note that the same icosi-edge also bisects a diamond face of the triaconta along its long diagonal axis - see 6.4).

- Icosi-edges
- 2-frequency triacon dome edges

The 2-frequency triacon breakdown defines the edges of both the rhombic triacontahedron and of the dodecahedron, but not of the icosahedron. Each imaginary edge of the icosahedron defines the long diagonal of a diamond-shaped face of the triacontahedron; the icosahedron has 30 edges - thus the triacontahedron has 30 faces. Each diamond face of the triacontahedron contains four LCD right-angled triangles - because the icosi-edge bisects the diamond face symmetrically into two sets of two LCD triangles each, the imaginary icosi-edge is theoretically in a perfect stress equilibrium.

Figure B.34 Diamond Face of Triacontahedron divided into four LCD triangles



The rhombic triacontahedron, upon which the original triacon breakdown is based, is a 'zonahedron', which implies that opposite edges of the diamond faces are parallel to each other - this allows for greater flexibility in design, because the dome can be stretched or compressed by adjusting a complete zone of parallel edges. Thus a triacon dome may be regarded as being a 'Zome', not a dome (see 6.4).

It is easier to divide a dome into a partial sphere by means of the alternate breakdown. In even frequencies an alternate dome with a vertex-zenith orientation has struts in alignment with a continuous great circle which divides the dome into a perfect hemisphere; thus no special base triangles have to be cut. In odd frequencies, the alternate breakdown defines no such continuous great circle lines which divide the sphere in half; however there are cut-off planes slightly above and slightly below the equator. These great circle lines produce  $3/8$ - and  $5/8$ -spheres respectively, although this terminology does not refer to the actual volume of the dome - it simply means that the one is less than hemispherical, the other more, and that the mean volume of the two equals the volume of a hemisphere of the same diameter. The more popular version of the alternate breakdown has  $3/8$ - and  $5/8$ -lines which are slightly uneven, resulting in domes which do not sit perfectly flat on a horizontal base (see 'DOME A'). However a 3-frequency 'truncatable' dome has been designed



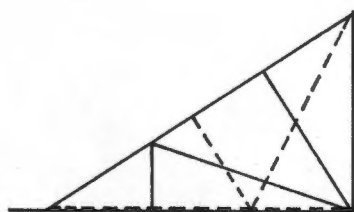
with perfectly horizontal cut-off planes at both the 3/8- and 5/8-mark (see 'DOME B').

The triacon breakdown is generally regarded as being ideal for larger domes of higher frequency because the number of different strut lengths in relation to frequency increases on a regular arithmetic scale, whereas the alternate breakdown requires relatively progressively more different strut lengths as the frequency of subdivision increases. However the variation in strut lengths for any particular frequency is less in the alternate than in the triacon breakdown, resulting in more equal triangles and producing smoother, more even curves.

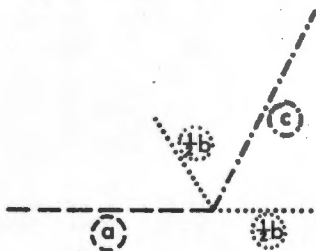
In the context of this study only the 3-frequency alternate and the 4-frequency triacon domes are considered as feasible alternatives for low-cost construction, because smaller frequencies produce components which are too large and cumbersome for easy handling; and higher frequencies result in too many different component-dimensions for economical mass production.

## B.7 Examples of Chord Factor Calculations by means of Napier's Rule

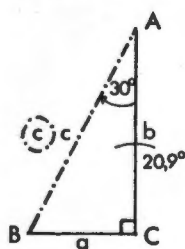
### B.7.1 Using a 3-frequency Alternate Breakdown: DOME A



—— LCD Triangle  
 ----- 3-frequency Alternate Breakdown superimposed



To solve chord length (c):



Having solved B:

$$\begin{aligned} A &= 30^\circ \\ b &= 20,9^\circ \\ \sin B^C &= \cos A^C \cos b \\ \cos B &= \sin A \cos b \\ &= \sin 30^\circ \cos 20,9^\circ \\ &= 0,467103 \\ B &= 62,154^\circ \end{aligned}$$

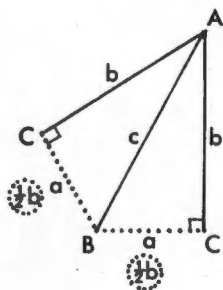
$$\begin{aligned} \sin c^C &= \tan A^C \tan B^C \\ \cos c &= \cot A \cot B \\ &= \cot 30^\circ \cot 62,154^\circ \\ &= 0,915002 \\ \textcircled{c} c &= 23,794^\circ \end{aligned}$$

To calculate chord factor for (c):

$$\begin{aligned} \textcircled{c} &= 2 \sin \frac{23,794^\circ}{2} \\ &= 0,412306 \end{aligned}$$

(Domebook 2: 0,412411)

To solve chord length (b):



To check:

$$\begin{aligned} A &= 30^\circ \\ b &= 20,9^\circ \\ c &= 23,794^\circ \end{aligned}$$

Since three variables are known we can solve and check

$$\begin{aligned} \sin b &= \tan A^C \tan a \\ \tan a &= \frac{\sin b}{\cot A} \\ &= \frac{\sin 20,9^\circ}{\cot 30^\circ} \\ &= 0,205963 \\ a &= 11,638^\circ \end{aligned}$$

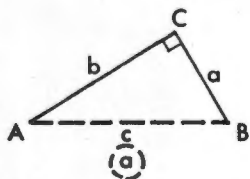
$$\begin{aligned} \sin a &= \cos A^C \cos c^C \\ &= \sin A \sin c \\ &= \sin 30^\circ \sin 23,794^\circ \\ &= 0,201725 \\ a &= 11,638^\circ \end{aligned}$$

To calculate chord factor for (b):

$$\begin{aligned} (b) &= 2 \left( 2 \sin \frac{11,638^\circ}{2} \right) \\ &= 0,405544 \end{aligned}$$

(Domebook 2: 0,403548)

To solve chord length (a):



Having solved b:

$$\begin{aligned} a &= 11,638^\circ \\ A &= 36^\circ \end{aligned}$$

$$\begin{aligned} \sin b &= \tan A^C \tan a \\ &= \cot A \tan a \\ &= \cot 36^\circ \tan 11,638^\circ \\ &= 0,283481 \\ b &= 16,468^\circ \end{aligned}$$

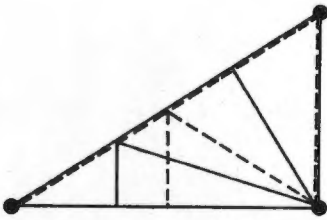
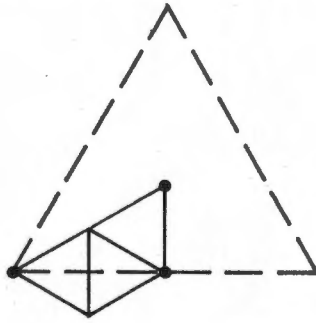
$$\begin{aligned} \sin c^C &= \cos a \cos b \\ \cos c &= \cos a \cos b \\ &= \cos 11,638^\circ \cos 16,468^\circ \\ &= 0,939263 \\ (a) c &= 20,072^\circ \end{aligned}$$

To calculate chord factor for (a):

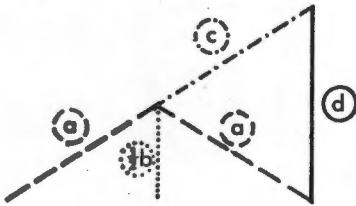
$$\begin{aligned} (a) &= 2 \sin \frac{20,072^\circ}{2} \\ &= 0,348534 \end{aligned}$$

(Domebook 2: 0,348616)

B.7.2 Using a 4-frequency Triacon Breakdown: DOME C

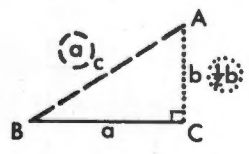


—— LCD Triangle  
 ----- 4-frequency Triacon  
 Breakdown superimposed



To solve chord length (a):

$$\begin{aligned} B &= 36^\circ \\ a &= \frac{31,7^\circ}{2} \\ &= 15,85^\circ \end{aligned}$$



$$\begin{aligned} \sin A^C &= \cos B^C \cos a \\ \cos A &= \sin B \cos a \\ &= \sin 36^\circ \cos 15,85^\circ \\ &= 0,565438 \\ A &= 55,568^\circ \end{aligned}$$

$$\begin{aligned} \sin c^C &= \tan A^C \tan B^C \\ \cos c &= \cot A \cot B \\ &= \cot 55,568^\circ \cot 36^\circ \\ &= 0,943581 \\ (a) c &= 19,338^\circ \end{aligned}$$

To calculate chord factor for (a):

$$\begin{aligned} (a) &= 2 \sin \frac{19,338^\circ}{2} \\ &= 0,335912 \end{aligned}$$

To solve chord length (b):

$$\begin{aligned}
 \sin b &= \cos c^C \cos B^C \\
 &= \sin c \sin B \\
 &= \sin 19,338^\circ \sin 36^\circ \\
 &= 0,194639 \\
 b &= 11,224^\circ
 \end{aligned}$$

To calculate chord factor for (b):

$$\begin{aligned}
 (b) &= 2 \sin \frac{11,224^\circ}{2} \\
 &= 0,391164
 \end{aligned}$$

(Domebook 2: 0,389480)

To calculate chord factor for (d):

$$\begin{aligned}
 (d) &= 2 \sin \frac{20,9^\circ}{2} \\
 &= 0,362754
 \end{aligned}$$

(Domebook 2: 0,362840)

To solve chord length (c):

$$\begin{aligned}
 (a) + (c) &= 37,38^\circ \\
 &= 37,38^\circ - a \\
 &= 37,38^\circ - 19,338^\circ \\
 &= 18,042^\circ
 \end{aligned}$$

To calculate chord factor for (c):

$$\begin{aligned}
 (c) &= 2 \sin \frac{18,042^\circ}{2} \\
 &= 0,313592
 \end{aligned}$$

(Domebook 2: 0,313370)

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Creative Structures, Inc., New Mexico  
Domaine, Maine  
Domebuilders Co., California  
Dome East, New York  
Domes and Homes, New Jersey  
Domes/Geodyssey Corp., Wisconsin  
Dome West, California  
Dyna Domes, Arizona



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